Trajectory Design and Vehicle Guidance for a Mid-Air Rendezvous between Two Autonomous Aircraft

by

Damien Jourdan

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

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Author ....
Department of Aeronautics and Astronautics
March 31st, 2003

Certified by ....
John J. Deyst
Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by ....
Edward M. Greitzer
H.N. Slater Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

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Abstract

The Parent Child Unmanned Air Vehicles (PCUAV) project is the fruit of a four year collaboration between M.I.T. and the Draper Lab. PCUAV aimed at providing close range observation from a distance using a low cost autonomous system. After defining the concept for the two first years, the PCUAV team focused on a key enabler of the system, the autonomous docking of two aircraft in mid-air.

This thesis presents the work done by the author regarding the development of avionics by which the two aircraft can autonomously be guided within 15m, one behind the other. The key features needed to achieve this goal are discussed. First, the design of the trajectory, to be followed by the chasing aircraft, is presented. Then, several options for the guidance of the vehicles are explored and the adaptation of Proportional Navigation for PCUAV is discussed. Finally, the synchronization required to bring the two vehicles in trail and 15m from each other is explained. Flight test results validating this work are also presented.

Thesis Supervisor: John J. Deyst
Title: Professor of Aeronautics and Astronautics

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And now "to Him Who is able to do immesurably more than all we ask or imagine,

according to His power that is at work within us", to the One Who brought me to Boston not only to earn a degree but for a greater purpose, that I may come to know Him personally and experience true life. Thank you Father for making this world so fascinating and for granting us some understanding about its laws - the more I study science and engineering the more I am amazed at how great You are - what an awesome God!

List of Acronyms

2D	Two Dimensions
3D	Three Dimensions
ATA	Avionics Testbed Aircraft
CG	Center of Gravity
DGPS	Differential Global Positioning System
I/O	Input/Output
IMU	Inertial Measurement Unit
GPS	Global Positioning System
GS	Ground Station
LOS	Line Of Sight
MAV	Micro Air Vehicle
MDPP	M.I.T./Draper Technology Development Partnership Program
MPIM	Mini Parent Interaction Mechanism
NGM	New Generation Mini
OHS	Outboard Horizontal Stabilizer
PCUAV	Parent and Child Unmanned Air Vehicle
PDV	Payload Delivery Vehicle
PN	Proportional Navigation
R/C	Remote Control
UAV	Unmanned Air Vehicle
WASP	Wide Area Surveillance Projectile

Chapter 1

Introduction

1.1 Background and Motivations

The Parent and Child Unmanned Air Vehicle (PCUAV) project is funded by the Charles Stark Draper Laboratory through the MIT/Draper Technology Development Partnership Program (MDPP), and is supervized at MIT by Prof. John Deyst. This partnership was created in 1996 to provide MIT students with an opportunity to work on a problem of significant interest to the U.S., and demonstrate the key enabling technologies relevant to its solution.

In the Fall of 1996, the Wide Area Surveillance Projectile project (WASP) was initiated through MDPP, to provide a canon-launched aircraft. WASP was terminated in 1998 and turned over exclusively to Draper for further development, which led to a tested prototype now being marketed by Draper.

In the Fall of 1998, the Draper Lab laid down a new tactical challenge for the research group. In very simple terms the requirement was to provide observation of an area at close range, from a distance. Prof. Deyst's illustration of the concept was that the system should be able to tell an operator sitting at MIT (in Boston) what was going on under a tree in Central Park (in New York City).

It was felt that the current trend in unmanned surveillance systems was towards sophisticated UAVs carrying very expensive equipment at high altitude. Therefore these systems, such as the U.S. Air Force Predator, tend to become more like “unmanned U2s”, which makes the requirement for autonomy unclear since the U2 is already available to perform such missions. Moreover, from a high altitude it is not possible to collect all of the information desired. Using the example cited above, it is difficult to observe what is happening on the Central Park Mall from 50.000ft because of the interfering tree canopy - even with the most advanced sensor. And it is altogether impossible to tell how many people are having dinner inside the Tavern on the Green! Therefore the usefulness of such observations leave much to be desired.

On the other hand, much effort is being spent in the UAV community to create small, highly maneuverable flying devices, the so-called Micro Air Vehicles (MAVs). These vehicles can fly under a tree canopy or come close to buildings, and can therefore observe from very close. However, their small size limits their data transmission power, and hence it is difficult and power-consuming to relay the information they gather to a high altitude plane or a satellite, thus limiting their usefulness. Furthermore, the limited energy reserves of such vehicles also severely limit their range of operation.

PCUAV aimed at providing a system that would safely (i.e. without endangering human lives) and at low cost bridge the gap between maneuverable but low power MAVs, and long range, long endurance and high altitude UAVs. The concept developed by the team during the first two years of the project was to create a three-tiered system consisting of:

- Tier 1 - A high altitude *Parent* unmanned aircraft;
- Tier 2 - Several *Child* (or *Minis*) unmanned aircraft at intermediate altitude;
- Tier 3 - MAVs, ground rovers, etc.

This system is illustrated in Figure 1.1.

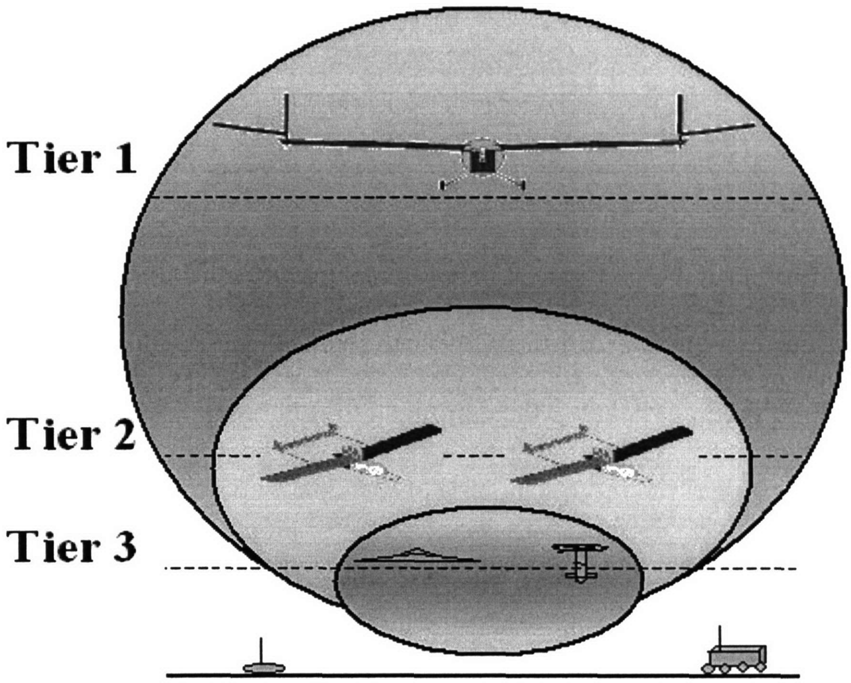


Figure 1.1 PCUAV Three-tiered System

The Parent transports Minis and MAVs to the mission site and deploys them. During the mission, the Minis serve as relays between the low power MAVs and the high altitude Parent. In turn, the Parent relays the real time information over long distances back to the home base. When the mission is completed, the Minis fly back to the Parent and dock with it - the reintegration phase - before the Parent flies back to the base. The concept of operation of PCUAV is decribed more in depth in Chapter 2.

From 2000 to the end of the summer of 2002, the team has focused its efforts on a key enabler of the PCUAV concept, the mid-air rendezvous and docking between the Mini and the Parent. In this effort, the author has worked on the trajectory planning, which serves to guide the Mini to within 15m behind the Parent.

1.2 Thesis Overview

This thesis will describe how, from any arbitrary initial position, the Mini creates a trajectory that brings it 15m behind the moving Parent, providing a good configuration for docking (details about the docking itself from this position can be found in [1] and [2]). Because of the team work involved in PCUAV, this thesis will make numerous references to the work of other team members. The author's main contribution to PCUAV has been to design a trajectory planner for the Mini that creates a path and robustly guides the airplane toward the Parent whenever the command to reintegrate is given.

Descriptions of the remaining chapters of this thesis are as follows.

Chapter 2 describes the PCUAV concept in greater depth and explains why reintegration is a key requirement for such a system. A brief description of the vehicles used for demonstration is also included.

Chapter 3 analyzes the requirements for a mid-air rendezvous and explains how the team divided the reintegration into two parts, Phase I and Phase II.

Chapter 4 describes the core of the trajectory planner, the design of the nominal path.

Chapter 5 focuses on the navigation of the Mini and how the trajectory designed in Chapter 4 was actually used.

Chapter 6 describes how the vehicles are synchronized in order to bring them close to each other, using the trajectory and guidance described in Chapters 4 and 5. Flight test results are also presented.

Chapter 2

The PCUAV System

2.1 Chapter Overview

This chapter begins with a description of the concept of operation of PCUAV, which shows the capabilities of the proposed system. Then, the discussion focuses on the docking of two UAVs and explains the importance of this feature for PCUAV. Finally, the vehicles and electronics used for the demonstration of reintegration are described.

2.2 The PCUAV Concept

2.2.1 Concept of Operation

The following describes a typical mission scenario using PCUAV.

An operator at the base desires to observe what is happening inside a building 100 miles away. He enters the coordinates of the point into the PCUAV system and from that point on the mission is autonomous. The Parent aircraft, carrying Minis and MAVs, takes off and flies to the mission site. It deploys all the vehicles and stays at high altitude, circling over the area of interest. Its size and altitude enable it to maintain a communication link with the base (via a direct link or a satellite).

The MAVs hover around the building, gathering the desired observation data. They transmit this information to the Minis that are flying at intermediate altitude which in turn pass it on to the Parent. The Parent is then able to relay it to the ground base.

The Minis and the Parent also perform mid and high altitude surveillance of the area, providing the base with observation from different levels.

Since the MAVs have a low life span due to their size and limitation in power, additional MAVs can be launched from the Parent in order to maintain the surveillance on the ground. Moreover, since the Minis are relatively small and cannot carry much fuel, they refuel at the Parent to extend the mission time.

The Minis can also be used to retrieve samples or sensors from the ground. Their maneuverability allow the Minis to fly accurately and catch a payload which would have been elevated from the ground via a balloon for example.

When the operator is satisfied with the amount of information gathered, or when the Parent reaches its power/fuel limit, the order is given for the system to return to its base. The MAVs on the ground are expendable and are left on site. However the Minis have a higher value and it is desired that they be retrieved. Since their range is limited they cannot fly back by themselves but perform a rendezvous with the Parent. Once they are docked-with the Parent, the Parent flies back to the base.

This mission is illustrated in Figure 2.1.

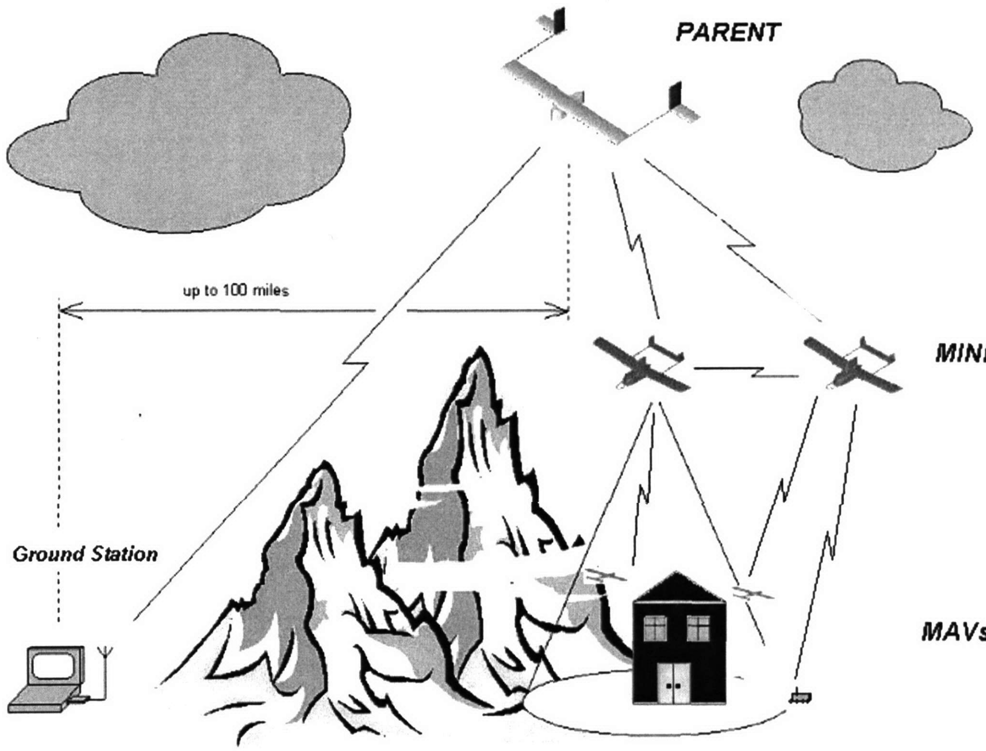


Figure 2.1 Building Observation using PCUAV

2.2.2 PCUAV Capabilities

The scenario described above shows that PCUAV achieves the following:

- Close-up surveillance relayed to a distant operator;
- Real-time tracking of a moving object enabled by the coverage from different altitudes;
- Sustained presence through the refueling of the Minis and the deployement of new MAVs. The mission length therefore goes beyond that of both vehicles if used individually;
- Sample or sensor retrieval with the Minis;

- Observation range of about 200km. The range of MAVs alone is very short since they can only transmit information a few kilometers at most. Likewise small maneuverable aircraft like the Minis cannot fly far because of their limited fuel storage capacity. PCUAV takes maximum advantage of the various vehicles' capabilities,
- Low cost - only the MAVs are expandable, the Minis and the Parent are retrieved;

Since high altitude UAVs (like the Predator) and maneuverable MAVs exist or are being developed, the team decided to focus its efforts on one specific key feature of PCUAV which seems to have been overlooked so far - the docking of two UAVs. Reintegration is the term used to designate the phase when the Child (Mini) flies to dock with the Parent.

2.3 The Importance of Reintegration

The importance of reintegration is best understood when considering what the difference would be if it was not done. The system would still be launched from the base, go to the mission site and perform observation just like the PCUAV system. However, refueling would not be possible for the Mini since it requires reintegration-like technology. The length of the mission would therefore be limited by the amount of fuel a Mini can carry. Once the mission is over, the Parent alone flies back to the base. The Minis are lost as well as information gathered onboard that could not be sent wireless, and no sample or sensor retrieval is possible.

The importance of reintegration is therefore threefold:

- Mission extension (via refueling);
- Sample/Information retrieval;
- Minimum mission cost by retrieving the Minis.

It seemed to the team that such a rendezvous capability did not exist. Aircraft docking is a reality between manned vehicles (e.g. air-to-air refueling) but has yet to be implemented between two UAVs. The control and guidance precision required without any human in the loop for that kind of operation is very challenging and is one reason why the team was highly motivated to tackle this problem. The subsequent discussion will therefore be aimed towards developing reintegration.

2.4 Reintegration Demonstration

A significant aspect of the PCUAV project is that from the beginning it was clear that the work would not only be theoretical, but it would also include some physical demonstration of the research. Since the team focused on docking - a quite complicated feature - a large amount of time and effort was devoted to the construction of the vehicles and the implementation of the theoretical work.

Diverse skills were required in the project, from the building of R/C airplanes to the wiring of avionics boxes. The following section briefly describes what hardware was chosen for demonstration.

2.4.1 Vehicles

Demonstrating the reintegration of several Minis on one Parent (as specified above in the objective system) implied a complicated building process (more Minis to build, larger Parent, etc.) and added a lot of complications expecially when it comes to the flight test management. Since docking is the key feature that PCUAV wanted to demonstrate, it was decided to use only one Mini - the adaptation of the docking technology for several Minis would be left for the developers of an objective system.

Therefore, two aircraft needed to be designed, one Parent and one Mini.

2.4.1.1 Parent Vehicle

The Parent aircraft needs to have a cleared area at the rear for the docking of the Mini, and therefore the tail section of an ordinary aircraft is problematic. This is why the unusual Outboard Horizontal Stabilizer (OHS) design was adopted (see Figure 2.2). This configuration offers advantages in terms of aerodynamic properties (most notably because the aircraft is inherently statically stable and its horizontal tails are lifting surfaces), but it was chosen for PCUAV mainly because the cleared space behind the fuselage enabled an easier interaction between the Parent and the Child.

Figure 2.2 Parent OHS Vehicle at Fort Devens Airport, MA

This OHS design was brought in the summer of 2000 by Sarah Saleh from the University of Calgary, where she worked on the OHS configuration in a project led by Prof. John Kentfield and Dr. Jason Mukherjee.

Sarah Saleh, Jason Kepler and Francois Urbain designed and built an OHS aircraft for PCUAV which first flew in the Spring of 2001.

A detailed account of the Parent properties, design, construction and flight testing can be found in [3] and [7].

2.4.1.2 Mini Vehicle

Two major features were sought in the design of the Mini vehicle:

- First, it was felt that the precision demanded for a docking maneuver required the Mini vehicle to have increased controllability. In order for an ordinary aircraft to correct its longitudinal position, banking is necessary before any change can be made. Likewise, if vertical corrections are needed, the aircraft needs to pitch before being able to change its altitude. These maneuvers take time and are hazardous to make when the Mini is within a few feet of the Parent - *quick* position error corrections are necessary (a more quantitative study of this requirement from a control point of view can be found in [1]).
- Second, since the Mini would be approaching the Parent from the rear, it must be a pusher airplane (where the propeller faces the rear of the aircraft).

These two main requirements drove the design of the Mini vehicle, done by Simon and Tony Evans, in the second year of the project, as shown in Figure 2.3.

One of the most exotic features of its design is the vertical fin on top of the wing. This fin provides the *direct side force* which enables the Mini to correct its longitudinal position without banking. Likewise, the use of flaperons gives the Mini *direct lift force* enabling it to perform altitude changes without pitching. These direct forces result from the close location of the control surfaces to the CG of the vehicle.

Figure 2.3 Mini Vehicle at Medfield, MA

The first version of the Mini was built in the second year of the project but was lost in an office fire in the Spring of 2000. A revised version of the Mini (called the New Generation Mini I (NGM I)) was built in the Summer of 2000 and flown R/C in the Fall of 2000. A lighter and larger version of the NGM (NGM II) was built in the Spring of 2001 to accomodate the increase in size and weight of the avionics package necessary for autonomous flights. It first flew R/C in the Summer of 2001, and was then used for the autonomous flights performed in the summer of 2002 and discussed in Chapters 5 and 6.

2.4.1.3 Avionics Testbed Aircraft (ATA)

Due to the complexity of the building of Mini vehicles, the team did not want to risk these aircraft during the in-flight testing of the avionics and software. For this purpose, an R/C kit airplane named Avionics Testbed Aircraft (ATA) was bought and modified to accomodate the avionics in its fuselage. It is shown in Figure 2.4.

Figure 2.4 Avionics Testbed Aircraft

When crashes occured, it was cheap and easy to build a new ATA. Several of them were used, and they proved very useful in order for the team to create a reliable avionics package and validate the software before testing it inside the valuable NGM II.

2.4.2 Electronics

An extensive discussion about the electronics hardware chosen for demonstration can be found in [3]. The main components of the avionics box placed inside the airplanes were:

- A PC104 computer stack
- A Canadian Marconi Allstar GPS receiver
- A MaxStream transceiver (wireless modem)
- An Inertial Measurement Unit
- Single Board Computers SBC 2000

- R/C receivers
- Analog to Digital converters

These components were fitted into an avionic box built by the team that could be rapidly placed or removed from the airplane. A picture of these boxes for the Mini and for the Parent can be seen in Figure 2.5.

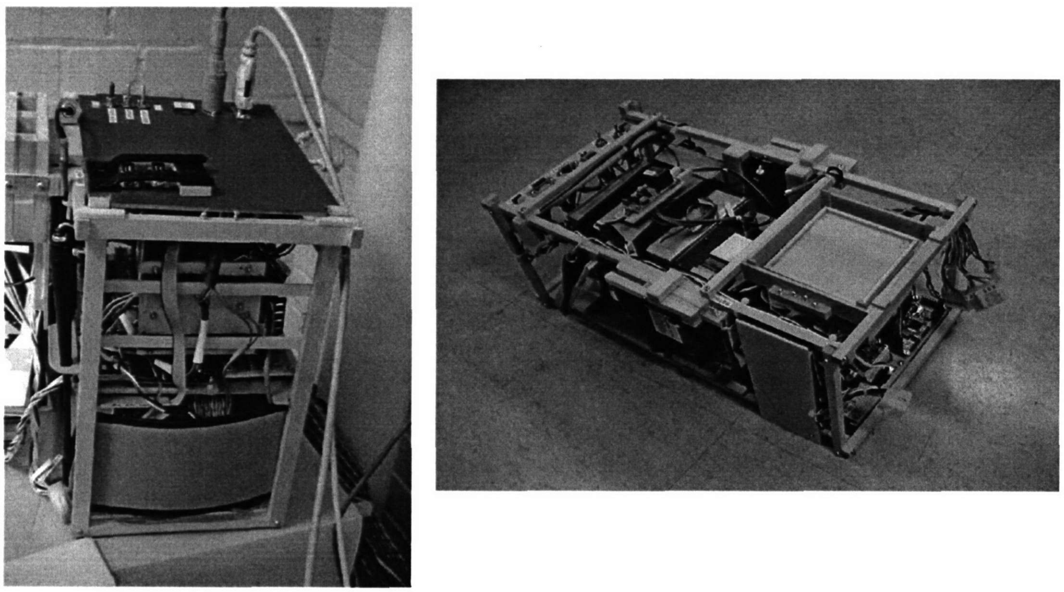


Figure 2.5 Avionics box of Parent (left) and Mini (right)

On the ground the team could monitor the status of each airplane through a laptop connected to a transceiver. This Ground Station is described more in depth in Chapter 6 and Appendix D. The communication between the Parent, the Mini, and the Ground Station for the demonstration of docking was implemented by Richard Poutrel [6].

2.5 Chapter Summary

This chapter began by describing a typical PCUAV mission. Then, the importance of reintegration between two UAVs was discussed as a justification for the focus of the PCUAV research. Finally, the vehicles and electronics developed by the team to demonstrate the docking were described.

The following chapter will focus on the requirements posed by a mid-air rendezvous and will introduce the strategy developed by the team, and the author, to achieve it.

Chapter 3

Aerial Rendezvous Analysis

3.1 Chapter Overview

This chapter analyzes the reintegration procedure. It begins by discussing the initial configuration of the vehicles. Then, the procedure is broken into two parts, Phase I and Phase II, which reflect two types of guidance strategies. Each phase is discussed along with its navigation system.

3.2 Initial Configuration

As discussed in the previous chapter, reintegration is needed for refueling and also when the mission is over so that the Mini and the Parent come back as a single unit. In the PCUAV setup, the Parent flies at high altitude while the Mini flies closer to the ground. Since the goal of the mission is to survey a specific area, it was assumed that the Parent circles over the area. However no constraint was put on the flight pattern of the Mini since its mission goals can range from communication relay to sample retrieval.

When the order for reintegration is given the configuration will therefore be:

- The Parent circling at high altitude;
- The Mini below, flying in any direction.

The initial configuration of the vehicles is depicted in Figure 3.1.

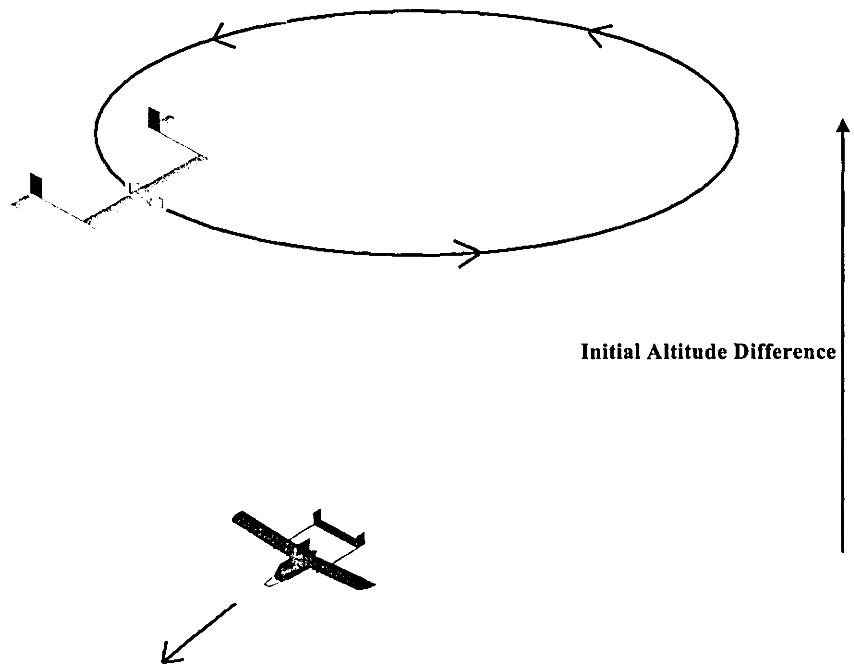


Figure 3.1 Initial Configuration of the Vehicles

The goal of a docking trajectory planner is therefore to create (for any initial configuration of the form described above) a procedure that would bring the Mini to the Parent. The following section discusses what information is needed for the vehicles to achieve this goal.

3.3 Information Needed

First of all, the vehicles need some navigation information in order to locate themselves. A knowledge of position and velocity is therefore a primary requirement for both aircraft.

More specific to reintegration the Mini needs to know the position of the Parent, otherwise it will be impossible for the Mini to approach the Parent and dock with it. This implies that both vehicle communicate with each other. Such a capability was implemented by Richard Poutrel [6] and will not be discussed in this thesis.

The following sections focus on the navigation information needed.

3.4 Navigation Information Accuracy Requirements

When the two vehicles are far from each other the need for accuracy in position information is not crucial. However, the closer they get to each other the more precise this information needs to be in order to bring them closer, as well as to prevent collision between the two vehicles. Since the need for navigation information accuracy varies during the reintegration procedure, the team decided to break it into two phases that reflect two levels of accuracy, Phase I and Phase II.

3.5 Phase I

By definition, the first of these phases, called Phase I, requires a low level of accuracy for navigation. Since Phase I achieves a rough approach of the Mini toward the Parent, a position accuracy of the order of a few meters is sufficient.

The team chose to use the GPS system for Phase I for the following reasons:

- The accuracy of its information fulfills the requirements stated above.
- GPS is likely to be used for the navigation of the vehicles during the whole mission, not only during reintegration.
- GPS is easy to use and standard enough to make its implementation well documented.
- The cost of a GPS receiver is very low compared to the price of the overall aircraft and its equipment.

The development of the GPS system for PCUAV was done by Richard Poutrel and an extensive discussion about it can be found in [6]. For the purpose of this thesis, the important factors are the accuracy of the GPS position information and its availability. This accuracy was estimated to be about 5m in the horizontal plane and 8m in the vertical plane. It should also be noted that the velocity information is very accurate, in the range of a few centimeters per second. Availability of GPS information is assured by access to many satellites, typically more than 5, and antennae effectively mounted on the vehicles.

It is clear that docking cannot be done using GPS only. When the distance between Parent and Mini comes close to the accuracy specifications of GPS (typically 10m), the aircraft cannot further rely on this information. Therefore, Phase I must stop before the Mini gets closer than 10m to the Parent and more accurate position information must be given to the Mini for its guidance towards the Parent. For demonstration it was decided that Phase I should bring the Mini about 15m behind the Parent. This distance is small enough so that the optical system of Phase II can detect the target, but large enough to maintain a safe separation between the Parent and the Mini so as to prevent collision due to the GPS inaccuracy. The author's work was to design a Phase I path planner that would guide the Mini during that phase.

3.6 Phase II

During Phase I both vehicles navigate using absolute position information. However, for docking what is really important is the relative position of the Mini with respect to the Parent. Therefore, once the Mini is behind the Parent (i.e. after Phase I is completed), accurate relative navigation of the Mini is sufficient to bring it in contact with the Parent. During the whole time the Parent would continue to use GPS to navigate.

In the two first years of preliminary design of PCUAV, the team decided to use a vision-based system to achieve this guidance. The initial concept was to use two cameras attached under the Mini wing in order to detect a red light attached on top of the Parent.

By stereovision the Mini would determine its relative position to the light. A discussion of this method is done by Sanghyuk Park in [1].

This system was tested on the ground, but a visible light system turned out to be too sensitive to ambient light conditions and the software and time needed for image processing was too large. In the Spring of 2002, Thomas Jones suggested the use of an infrared pulsing light system and this sytem was implemented by the team. Figure 3.2 illustrates the Phase II guidance.

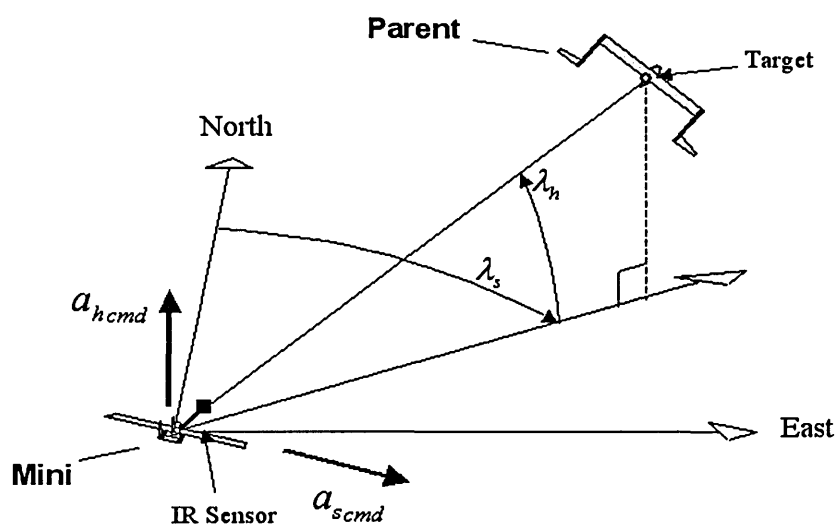


Figure 3.2 Phase II Guidance System

An array of infrared LEDs (Target) pulses on the Parent and an IR sensor placed in the nose of the Mini determines the XY position of the pulse with respect to the Mini body frame. The Mini is therefore able to calculate the line of sight (LOS) to the Parent (λ_s and λ_h) and it uses it to generate two accelaration commands $a_{s_{cmd}}$ and $a_{h_{cmd}}$ to guide itself towards the target. This is described in depth in [2].

A third possibility was to use some variant of Differential GPS (DGPS). Richard Poutrel [6] developped a code for PCUAV improving the accuracy of basic GPS, but the gain in accuracy was small compared to the added complexity of the code and therefore the optical sensor idea was kept.

3.7 From Contact to Docking

As mentioned before, Phase II brings the Mini from 15m behind the Parent to actual contact. When this contact occurs, a mechanism needs to secure it. Carmen Carreras built a truss called the Mini Parent Interaction Mechanism (MPIM) that achieves this. As can be seen on Figure 3.3, the MPIM includes a cone designed to catch the probe placed in front of the Mini. The red target used in Phase II can be seen attached on top of the cone.

Figure 3.3 Parent Vehicle with MPIM

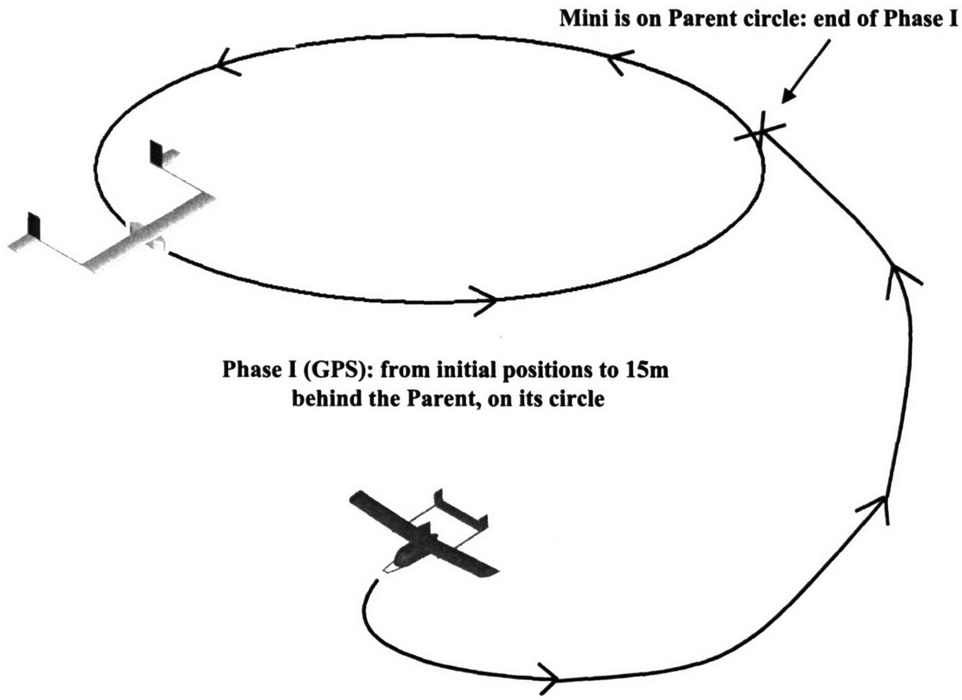
The flight dynamics of the Parent with the Mini attached to it through the MPIM are complicated and require an in-depth study. Since the work of the team focused on the guidance of the Mini toward the Parent, no work was spent on this problem. The team therefore decided to forsake actual contact between the two vehicles and rather prove that the Mini could be brought within a few meters of the Parent. Further study on this problem was left to the future developers of an objective system.

As a consequence Phase II for demonstration brings the Mini from 15m to a few meters of the Parent.

3.8 Chapter Summary

This chapter opened with a description of the initial configuration when the reintegration procedure begins. The division of the procedure into two phases, called Phase I and Phase II, was then justified in terms of the navigation accuracy requirement. During Phase I, the Mini uses GPS to navigate in order to position itself 15m behind the Parent. From this point Phase II begins and the Mini uses an optical sensor to guide itself to within a few meters of the Parent.

The reintegration procedure has now been explained and is summarized in Figure 3.4. The remainder of this thesis will focus on Phase I. Chapter 4 describes the design of the trajectory.



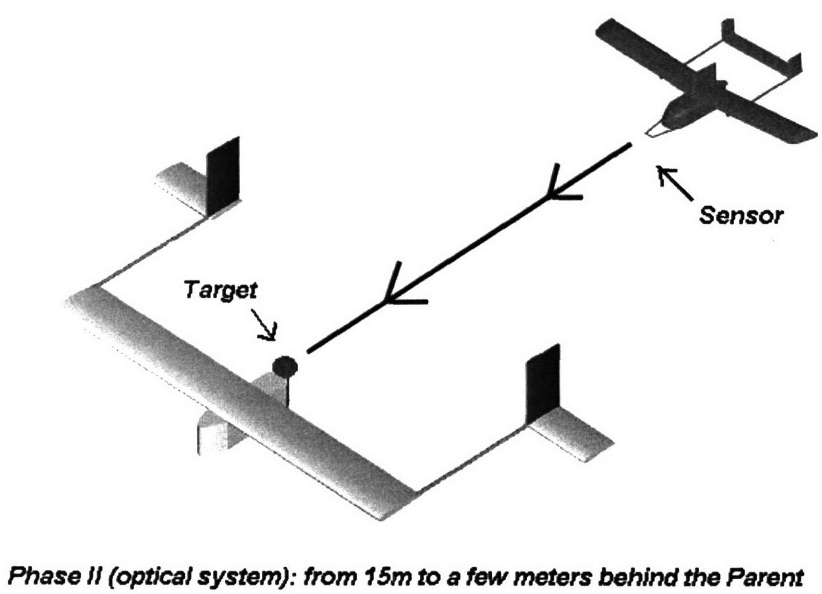


Figure 3.4 Reintegration Procedure Summary: Phase I (top) and Phase II (bottom)

Chapter 4

Trajectory Design for Phase I

4.1 Chapter Overview

This chapter describes the approach for designing a trajectory for Phase I. The control system will be examined to determine how it affects the maneuverability of the aircraft. Then, a trajectory will be built step by step using basic geometric elements like straight lines and curves. This build-up procedure will be standardized for the trajectory of Phase I, so that it will be the same whatever the initial conditions are, but first an analysis of the intial vehicle configuration will outline the top level objectives that need to be fulfilled by the trajectory.

4.2 Basic Requirements for the Trajectory

In most of the chapter the emphasis will be put on the demonstration system developed by the team which is based on two R/C aircraft. Section 4.7 will briefly discuss how the trajectory design would change by taking into account the operating conditions of the objective system.

A few basic requirements emerge when looking at the initial configuration of the vehicles, as discussed in Chapter 3. It is assumed that the Parent is passive and keeps circling the whole time.

Since the Parent flies at a higher altitude, the Mini first needs to gain altitude to reach the same level as the Parent. Second, the Mini must get into the Parent circle which implies that it should arrive tangentially to the circle (see Figure 4.1) and turn in the trigonometric direction, just like the Parent. Finally, the Mini must get in the circle *at the right time*, so that it is positioned just behind the Parent: this is what is called the *synchronization* between the two aircraft. The Mini trajectory must be optimized so that it does not reach the circle when the Parent is at its opposite end for example, otherwise it would take a long time for the Mini to catch up with the Parent. Figure 4.1 shows three scenarios of final configuration; the third one is the desired one.

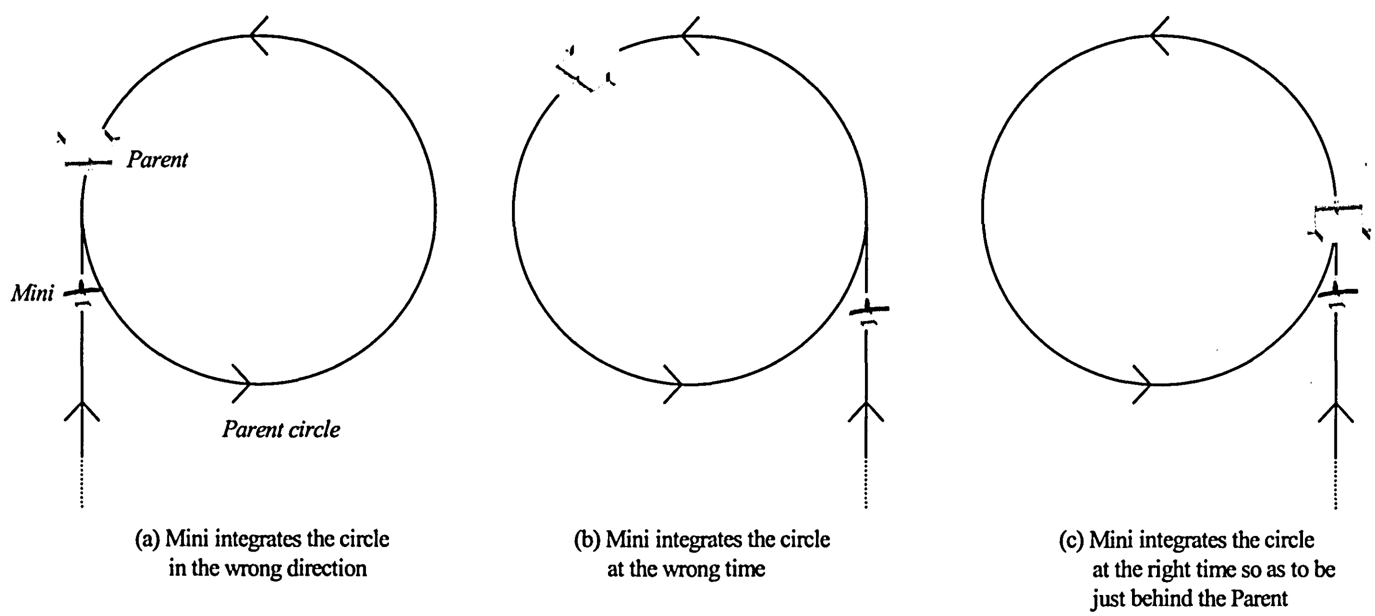


Figure 4.1 Possible positions of the Mini and the Parent at the end of Phase I

4.3 Finding a Standard Trajectory

4.3.1 Maneuverability Constraints

Before any work was done on Phase I, Sanghyuk Park had created the Mini control system for Phase II [1]. The design of this autopilot involved a linearized model of the aircraft dynamics which constrained the maneuverability of the vehicle. It was decided to use the same contraints to design the Phase I trajectory, so that the computed path would not require the Mini to perform maneuvers outside of its linear region. These constraints are now described.

A first constraint dictated by the control system is that the nominal bank angle for turns is about $10°$. This means that the vehicle cannot engage into steep turns, which limits its ability to make rapid heading corrections. This condition translates into a constraint on the radius of the turn R:

$$R = \frac{V^2}{\tan(\phi)g}$$

Since $\phi = 10°$ and that the approximate nominal velocity of the Mini is $V = 20\mathrm{ms}^{-1}$, the nominal turn radius R is about 231m. The turn radius for both vehicles was set at 250m.

Second, the aircraft cannot pitch too much. It was decided to climb of about 10m every time 100m is flown in the horizontal plane. This implies a climb angle of:

$$\gamma = \mathrm{atan}\left(\frac{10}{100}\right) = 5.7°$$

The team decided to set the climb angle at $6°$.

These two constraints shape how the vehicles turn and how they gain altitude, providing useful information to build the path.

4.3.2 First Approach: 3 Basic Trajectory Elements

It has been emphasized that Phase I should deal with any initial configuration of the vehicles, which implies that the path design must be flexible to initial conditions. In order to achieve this flexibility, it was decided to build a trajectory by assembling elementary building blocks together. These available blocks are:

- straight lines;
- climbs (at $6°$);
- turns at a constant radius (250m).

Following the requirements stated in 4.2 the following strategy was chosen:

- a *climb* to reach the required altitude;
- a *turn* to make the Mini head towards the desired point on the Parent circle, that is the tangential point to the Parent circle which makes the Mini turn in the trigonometric direction;
- a *straight line* to the target.

Whatever the initial heading or position of the vehicles is, a path bringing the Mini on the Parent circle can always be divided into these three basic elements. This is illustrated in Figure 4.2.

Doing this brings the Mini on the circle. But as already mentioned, it is not enough for the Mini to be on the circle, it must also be 15m behind the Parent. Since the Parent is passive and flies at a constant velocity, to achieve this synchronization the only available parameter to vary is the velocity of the Mini.

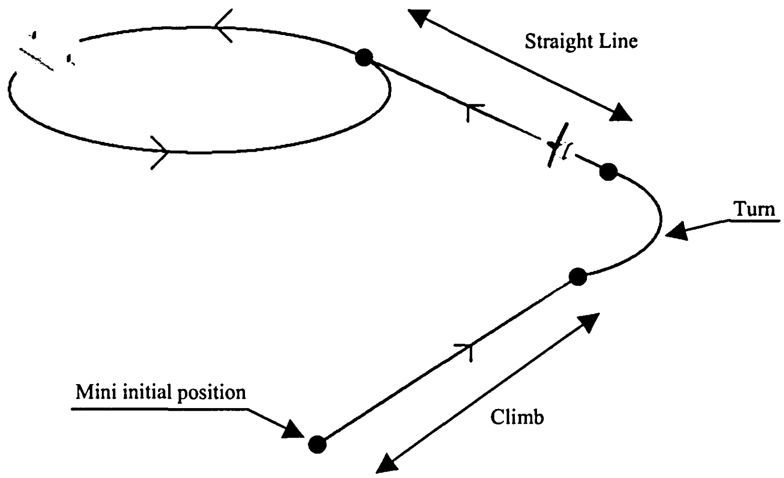


Figure 4.2 Phase I path using 3 elementary trajectory blocks

Finding a suitable velocity for the Mini to hold is possible, however in certain cases - depending on the initial configuration – the required velocity is too low (below the stall speed) or too high. This happens, for example, when the Mini is close to the Parent circle initially so that the trajectory is short, while at the same time the Parent is at the other end of its circle. In this case the Mini must fly very slowly in order to let the Parent catch up, which makes the Mini stall.

In order to ensure synchronization between the two vehicles in any initial configuration, some changes must be made. Since velocity control to ensure synchronization is not possible all the time, the trajectory itself must be changed to accomodate any initial configuration; another elementary trajectory block needs to be added.

4.3.3 Second Approach: 4 Basic Trajectory Elements

The addition of a straight line called L_1 between the climb and the turn solves the synchronization problem. The Phase I trajectory consists now of these four elements, as shown in Figure 4.3:

- a *Climb*;
- a *Straight Line* - L_1 ;
- a *Turn*;
- a S*traight Line*.

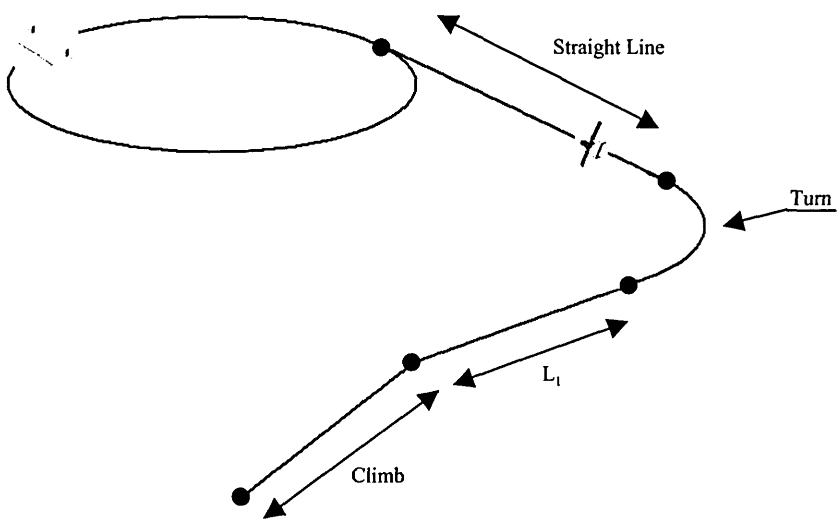
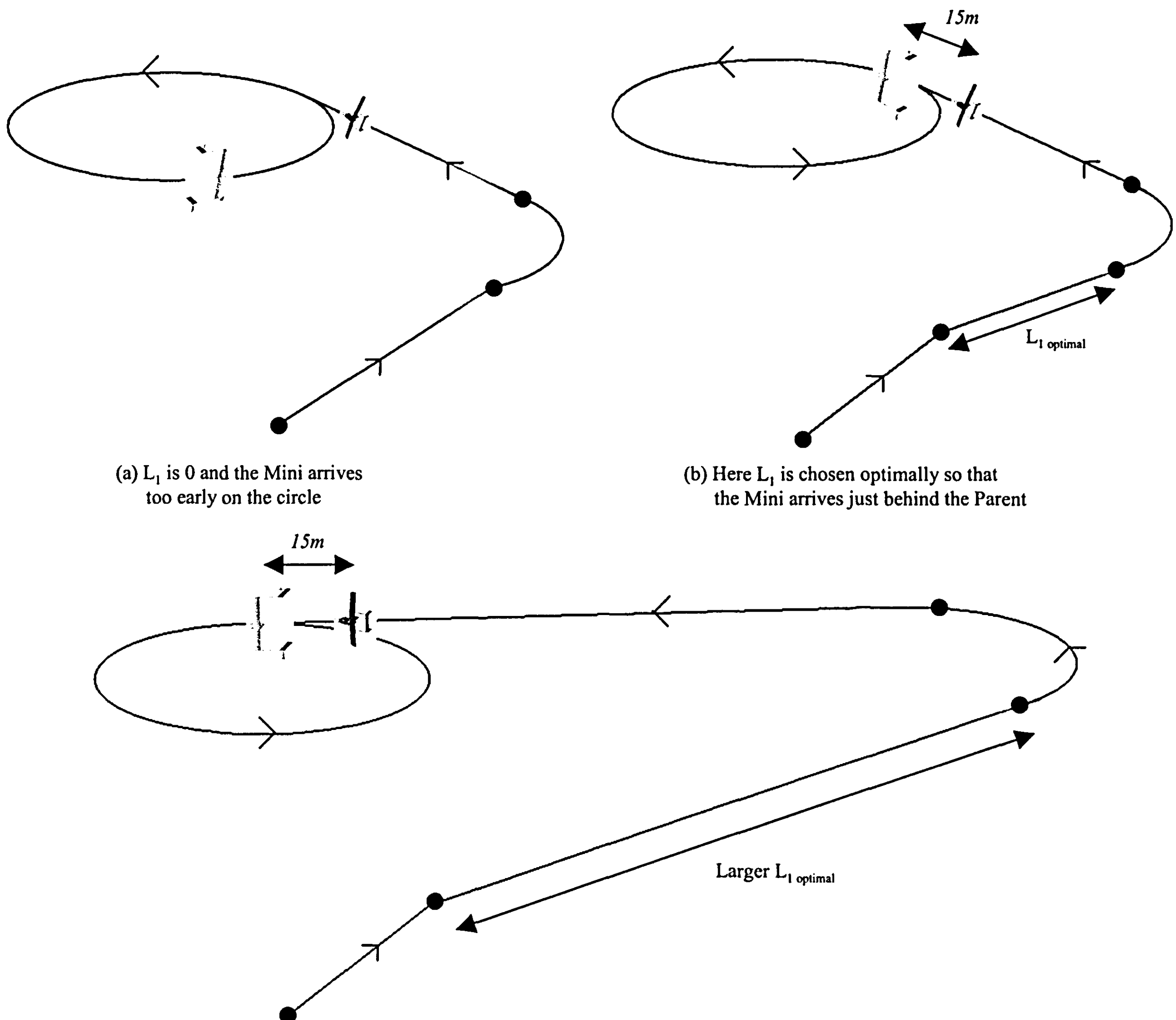


Figure 4.3 Phase I path using 4 elementary trajectory blocks

Assuming the velocities of the two vehicles to be *constant*, it is always possible to find L_1 so that the vehicles achieve the desired final configuration. This is easy to understand by putting L_1 equal to zero. In this situation, the computed trajectory brings the Mini on the circle (this is equivalent to the three element strategy presented in 4.3.2), but it is highly unlikely that the Parent will be 15m ahead of the Mini. If the Parent is behind the Mini, increasing L_1 will give time for the Parent to catch up with the Mini future arrival point, as illustrated in Figure 4.4. In figure (a) L_1 is zero and the Mini arrives too early on the circle. Increasing L_1 allows the Parent to catch up and figure (b) shows that an optimal value for L_1 exists that makes the separation between Parent and Mini exactly 15m.



(a) L_l is 0 and the Mini arrives too early on the circle

(b) Here L_l is chosen optimally so that the Mini arrives just behind the Parent

(c) Larger value of L_l that still guarantees the final separation of 15m

Figure 4.4 Influence of L_1 on the final configuration

It should be noticed that the choice of L_1 is not unique. Calling L_{1_0} the value found above, if a value of L_1 larger than L_{1_0} is chosen, it is still possible to have the final synchronization if the Parent performs an additional revolution on its circle. A new optimal value for L_1 is found as shown on Figure 4.4(c). This is discussed more in 4.5.2. In practice, the smallest value of L_1 will be used in order to make the reintegration duration as small as possible.

This four steps trajectory works for any initial configuration and was therefore chosen as the strategy for the demonstration of Phase I. The following section describes the analytic approach to determine the trajectory.

4.4 Calculation of the Waypoint Coordinates

The trajectory described in the previous section is completely characterized by five points called M_i, M_0, M_1, M_2 and M_3. They represent respectively the points at the intial time, at the end of the climb, at the end of L_1, after the turn, and at the end of Phase I (on the Parent circle). An additioinal point M_c is defined as the center of the Mini turn. Its position can be found using the five previous waypoints. The goal of this section is to determine analytically the coordinates of these waypoints.

The time taken by each step will also be calculated assuming a constant velocity V for the Mini. These times will be noted T_0 (climb), T_1 (L_1), T_2 (turn) and T_3 (straight line). They will be important in the next section for the numerical determination of L_1.

4.4.1 Notations

The following conventions and notations will be used in the remainder of the chapter:

- (X,Y,Z) is a frame where the Z-axis points up (altitude axis);
- The Z axis passes through the center O of the Parent circle;
- $R = 250m$ is the radius of the turns;
- Ψ is the heading of the aircraft in the (X,Y) plane positive in the trigonometric direction with respect to the X-axis;

- V_{mini} and V_{parent} are the velocities of the Mini and the Parent. For the moment *these velocities are assumed to be constant*;
- $(X_{M_i}, Y_{M_i}, Z_{M_i})$ and $(X_{P_i}, Y_{P_i}, Z_{P_i})$ are the initial (i.e. when Phase I begins) coordinates of the Mini and the Parent in the (X,Y,Z) frame;
- Ψ_{P_i} and Ψ_{P_3} are the respective heading angles of the Parent at the initial time and when the Mini is in M_3;
- Ψ_{M_i}, Ψ_{M_0}, Ψ_{M_1}, Ψ_{M_2} and Ψ_{M_3} are respectively the heading angles of the Mini at the points M_i, M_0, M_1, M_2 and M_3. It should be noticed that Ψ_{M_i}, Ψ_{M_0} and Ψ_{M_1} are equal since until the turn the Mini keeps a constant heading.
- θ_2 is the turn angle of the Mini which represent the change in heading perfomed during its turn.

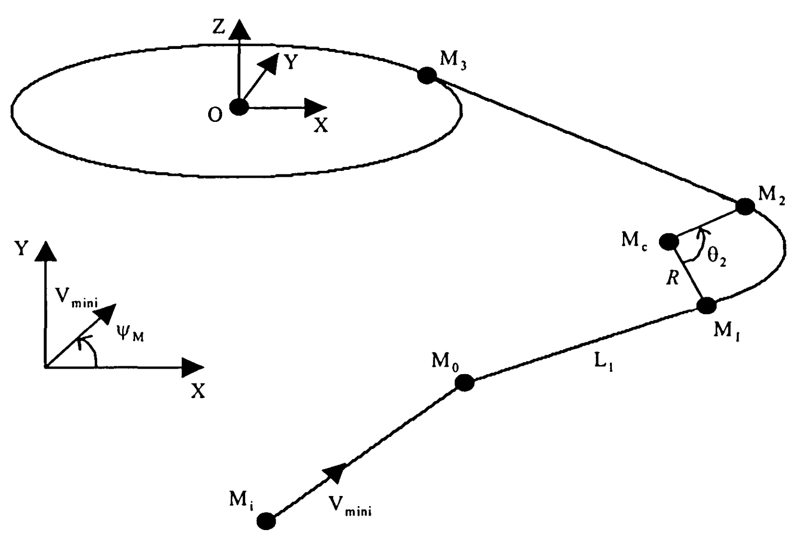


Figure 4.5 Notations

4.4.2 Climb

Initially, the Mini heading is Ψ_{M_i} and it climbs at an angle $\gamma = 6°$ to reach the altitude Z_{P_i} (the Parent holds its altitude the whole time). This completely determines the climb and the coordinates $(X_{M_0}, Y_{M_0}, Z_{M_0})$ of the arrival point M_0 after the climb are:

$$X_{M_0} = X_{M_i} + \frac{Z_{P_i} - Z_{M_i}}{\tan(\gamma)} \cos(\Psi_{M_i}) \qquad Y_{M_0} = Y_{M_i} + \frac{Z_{P_i} - Z_{M_i}}{\tan(\gamma)} \sin(\Psi_{M_i})$$

$Z_{M_0} = Z_{P_i}$ since at the end of the climb the two aircraft have the same altitude.

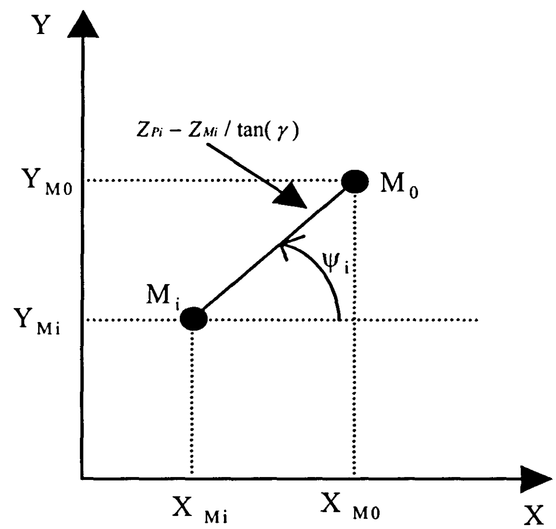


Figure 4.6 M_0 coordinates calculation

The time T_0 required to reach M_0 is:

$$T_0 = \frac{Z_{P_i} - Z_{M_i}}{V \sin(\gamma)}$$

4.4.3 L_1

Likewise, the coordinates of the point M_1 after the straight line L_1 can be calculated:

$$X_{M_1} = X_{M_0} + L_1 \cos(\Psi_{M_i})$$

$$Y_{M_1} = Y_{M_0} + L_1 \sin(\Psi_{M_i})$$

$$Z_{M_1} = Z_{P_i}$$

with a flight time of:

$$T_1 = \frac{L_1}{V}$$

4.4.4 Turn

In order to determine the coordinates of M_2 and the turn angle θ_2, the point M_c needs to be obtained. To calculate the coordinates of M_c, a new frame of reference is defined with coordinates X', Y'. This new frame is rotated by the angle Ψ_{M_i}, so as to align the X' axis with the initial heading of the Mini as it enters the turn, and its origin is at M_1. Thus, if the coordinates of any point in the space are (X, Y) in the original frame, and (X', Y') in the new frame, these are related by

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos(\Psi_{M_i}) & -\sin(\Psi_{M_i}) \\ \sin(\Psi_{M_i}) & \cos(\Psi_{M_i}) \end{bmatrix} \begin{bmatrix} X' \\ Y' \end{bmatrix} + \begin{bmatrix} X_{M_1} \\ Y_{M_1} \end{bmatrix}$$

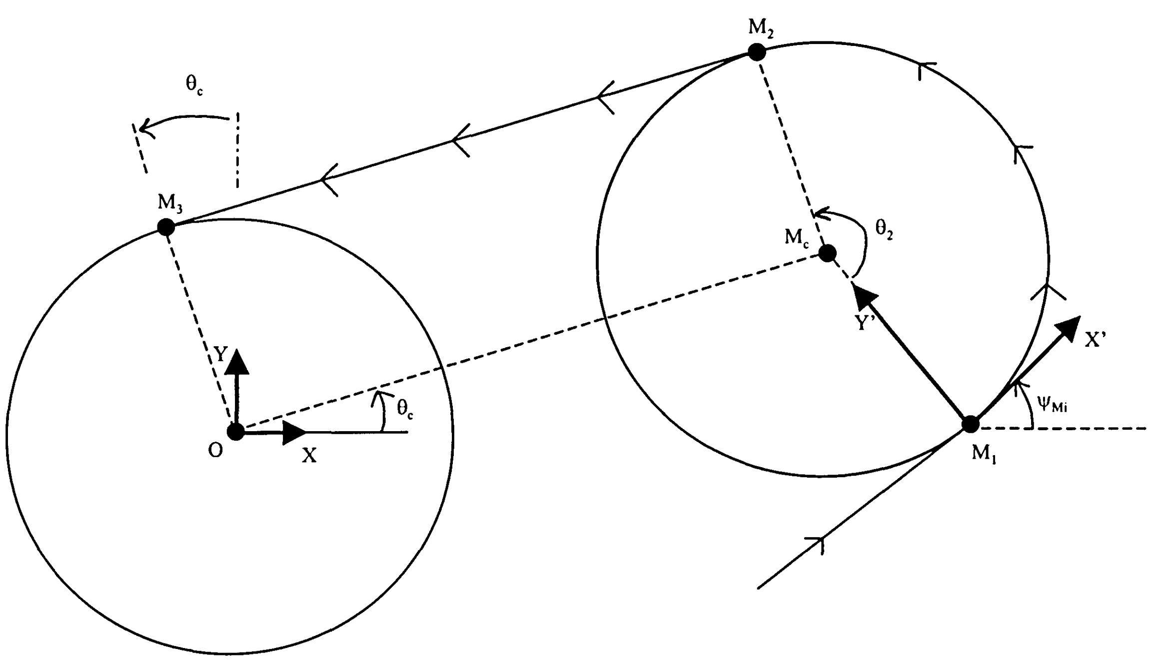


Figure 4.7 Frame rotations to find M_c, M_2 and the turn angle θ_2

In the new frame, the center of the turn is simply $\begin{bmatrix} X' \\ Y' \end{bmatrix} = \begin{bmatrix} 0 \\ R \end{bmatrix}$ which gives M_c in the original frame:

$$\begin{aligned} X_c &= -R\sin(\Psi_{M_i}) + X_{M_1} \\ Y_c &= R\cos(\Psi_{M_i}) + Y_{M_1} \end{aligned}$$

To obtain the coordinates of M_2, another frame definition is necessary. This time the frame origin is placed at M_c and the rotation angle is $\theta_c = \mathrm{atan}(Y_c, X_c)$. Since both circles have the same radius, the line segment from the original origin to M_c is parallel to the line tangent to the two circles. Therefore, the escape point from the turn circle must have the coordinates $\begin{bmatrix} X'' \\ Y'' \end{bmatrix} = \begin{bmatrix} 0 \\ R \end{bmatrix}$ in the new frame. This gives the coordinates of M_2:

$$\begin{aligned} X_{M_2} &= -R\sin(\theta_c) + X_c \\ Y_{M_2} &= R\cos(\theta_c) + Y_c \end{aligned}$$

To calculate the turn angle θ_2, the frame of reference should be centered at M_c and rotated so that the X-axis is aligned with the line segment from M_c to M_1. Therefore, a rotation of

$$\delta = \mathrm{atan}(Y_{M_1} - Y_c, X_{M_1} - X_c)$$

is necessary. In this frame the new coordinates of M_2 are:

$$\begin{aligned} X'_{M_2} &= (X_{M_2} - X_c)\cos(\delta) + (Y_{M_2} - Y_c)\sin(\delta) \\ Y'_{M_2} &= -(X_{M_2} - X_c)\sin(\delta) + (Y_{M_2} - Y_c)\cos(\delta) \end{aligned}$$

θ_2 is obtained by calculating $\theta_2 = \mathrm{atan}(Y'_{M_2}, X'_{M_2})$. If this quantity is negative it implies a turn of more than $180°$, so that $360°$ should be added to this number.

The time of travel during the turn is $T_2 = \frac{R\theta_2}{V}$.

4.4.5 Second Straight Line

The only remaining coordinates to find are those of M_3, the point of arrival on the Parent's circle. The same type of frame rotation as used to find M_2 can be performed, except that now the origin would stay at O. This leads to:

$$X_{M_3} = -R\sin(\theta_c)$$
$$Y_{M_3} = R\cos(\theta_c)$$

The distance between M_2 and M_3 is the same as the distance between O and M_c. Therefore, the time T_3 during this straight flight is:

$$T_3 = \frac{\sqrt{X_c^2 + Y_c^2}}{V}$$

The total time of Phase I is obtained by adding all the flight times:

$$T_{total} = T_0 + T_1 + T_2 + T_3$$

4.4.6 Summary

Every waypoint has now been analytically determined. They can be numerically calculated, provided the following information is given:

- Initial position M_i;
- Initial heading Ψ_{M_i};
- L_1.

The first two are initial conditions that will be provided to the trajectory planner when Phase I begins, whereas L_1 needs to be computed. The next section describes the algorithm used to calculate the optimal value of L_1. In this calculation the Parent information will be needed.

4.5 Calculation of L_1

To determine the L_1 value that will bring the Mini 15m behind the Parent, a numerical method is used.

Given the initial position and heading of the Mini and a value for L_1, the final position of the vehicle on the Parent circle can be calculated using the formulas stated in the previous section. The Parent is assumed to fly at a constant velocity on its circle so that given its initial position, its future position at any time can be calculated. Since in 4.4 the time needed for Phase I was calculated, it is possible to know the position P_3 of the Parent at the end of Phase I.

As a consequence for any value of L_1 the final positions of the two aircraft can be numerically calculated. The purpose of the optimization described below will be to find the value of L_1 that brings the Mini exactly 15m behind the Parent.

4.5.1 The Cost Function

To solve this optimization problem a cost function will be minimized. For Phase I the important factor is how far apart on the circle the aircraft are at the end of Phase I, as well as their respective order - the Parent must precede the Mini. For each value of L_1 the corresponding M_3 and P_3 are calculated. The cost chosen is the absolute value of the distance between the potential M_3 and a point on the circle 15m behind P_3. By minimizing this cost to zero the desired distance and order between the vehicles will be achieved. This is illustrated in Figure 4.8.

The cost is a function C of L_1.

$$\text{Cost} = C(L_1)$$

Given a numerical value of L_1, all the waypoints are numerically calculated using the analytic formulas given in 4.4. These formulas give the numerical coordinates of M_3 $\left\{X_{M_3}(L_1), Y_{M_3}(L_1)\right\}$.

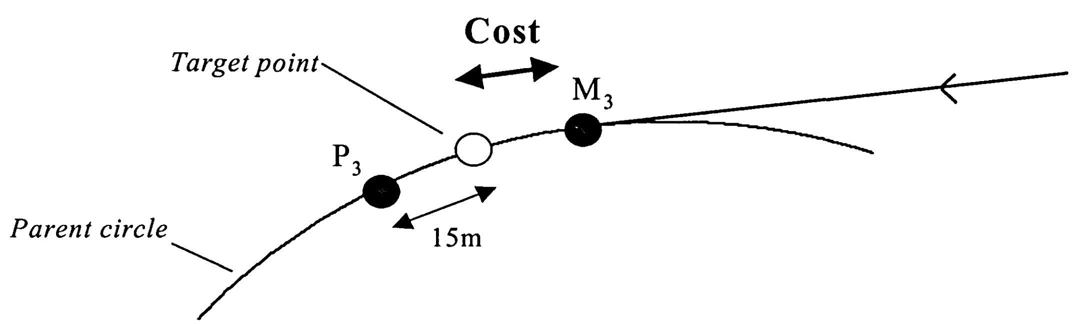


Figure 4.8 Cost Function

Knowing T_{total} also determines the final position of the Parent by calculating its final heading:

$$\Psi_{P_3}(L_1) = \Psi_{P_i} + \frac{V \cdot T_{total}(L_1)}{R}$$

The coordinates of the target point 15m behind the Parent are obtained:

$$X_{target}(L_1) = R\cos\left(\Psi_{P_3}(L_1) - \frac{15}{R} - \frac{\pi}{2}\right)$$

$$Y_{target}(L_1) = R\sin\left(\Psi_{P_3}(L_1) - \frac{15}{R} - \frac{\pi}{2}\right)$$

Everything is now at hand to calculate the cost function:

$$Cost = C(L_1) = \sqrt{(X_{M_3} - X_{target})^2 + (Y_{M_3} - Y_{target})^2}$$

A cost can now be associated with each value of L_1. The remaining of the section presents the algorithm used to minimize this cost.

4.5.2 The Minimization Algorithm

Linear bisection was used to find the value of L_1 that minimizes C. For this algorithm to start, two initial input values must be chosen that will bound the search.

The choice of these bounds is important in order for the optimization to succeed. For a given set of initial conditions the behavior of C can be plotted. Figure 4.9 shows a typical plot of the cost C versus L_1 and two trajectories, depending on which optimal value of L_1 is chosen. These trajectories are obtained using MATLAB.

The oscillatory behavior of C shows that an infinity of values of L_1 minimize C, which bring Parent and Mini in the required final configuration. This was already discussed in 4.3.3 and, as mentioned before, the goal for Phase I is to select the smallest of these values in order to minimize the length of reintegration.

It can also be seen from Figure 4.9 that if the initial bounds of the algorithm are badly chosen, the algorithm will not converge to the right solution. If the bounds are chosen too far apart, there will be several minima of C and the algorithm may not converge to the right solution. If, on the other hand, the bounds are close to each other, they may not include the optimal value of L_1.

The boundary values must therefore be chosen so that there is one, and only one, solution between them, and it must be the smallest one. To find these boudary values C is calculated starting from an input of L_1=0 and increasing it by increments of 50 meters. A minimum occurs when deacreasing values of C are followed by increasing ones. The boundaries are the values around this point: the optimal value for L_1 lies between these two. Linear bisection is then used to find the optimal value of L_1. More graphs showing different shapes of Phase I trajectories are included in Appendix A.

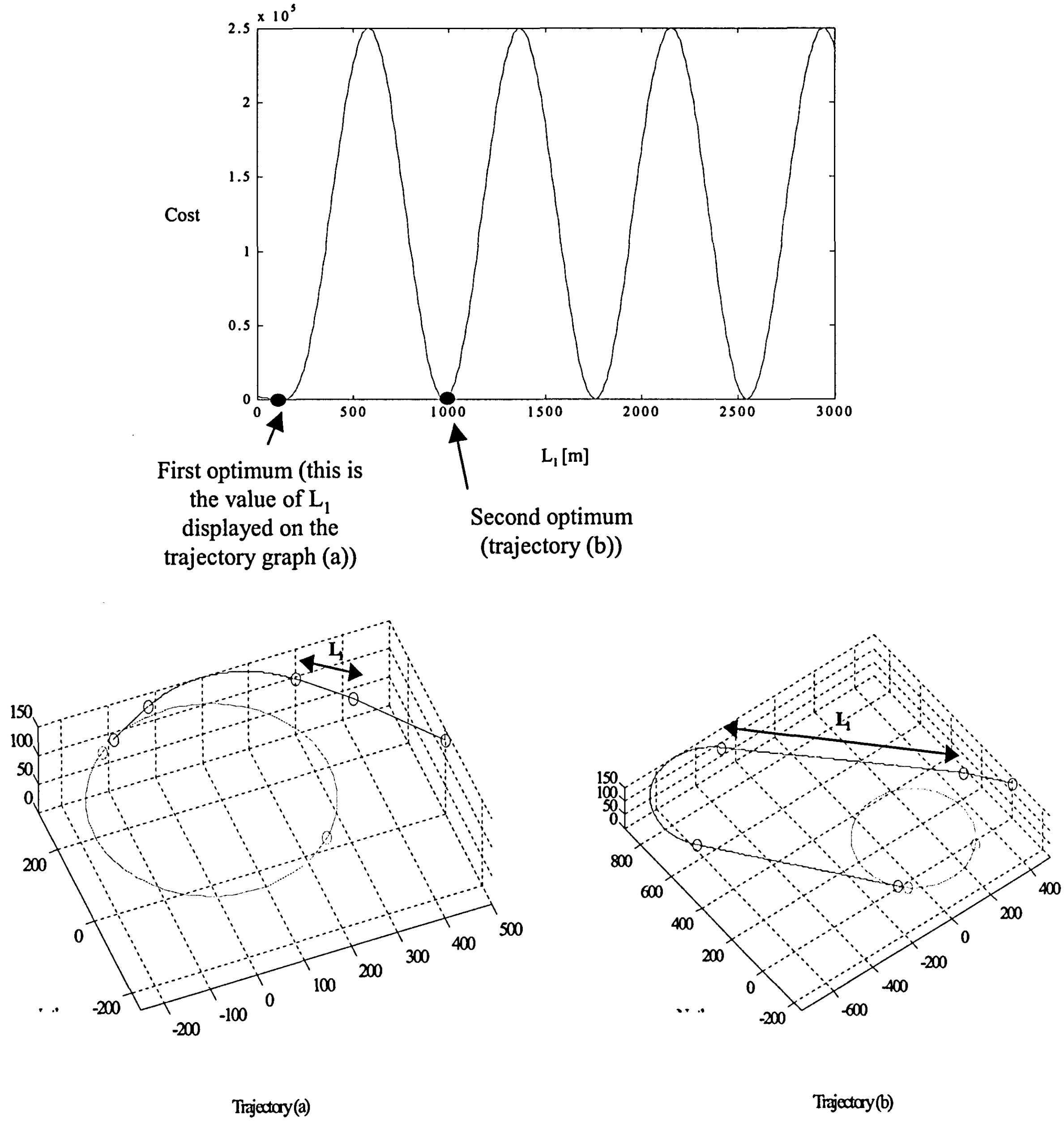


Figure 4.9 Plot of Cost vs L_1 and the corresponding paths depending on the choice of L_1

4.6 Collision Risks

When the Mini trajectory intersects the Parent circle, there is a risk of collision between the two vehicles. Such a situation can happen if the Mini initially heads toward the Parent circle, as shown in Figure 4.10.

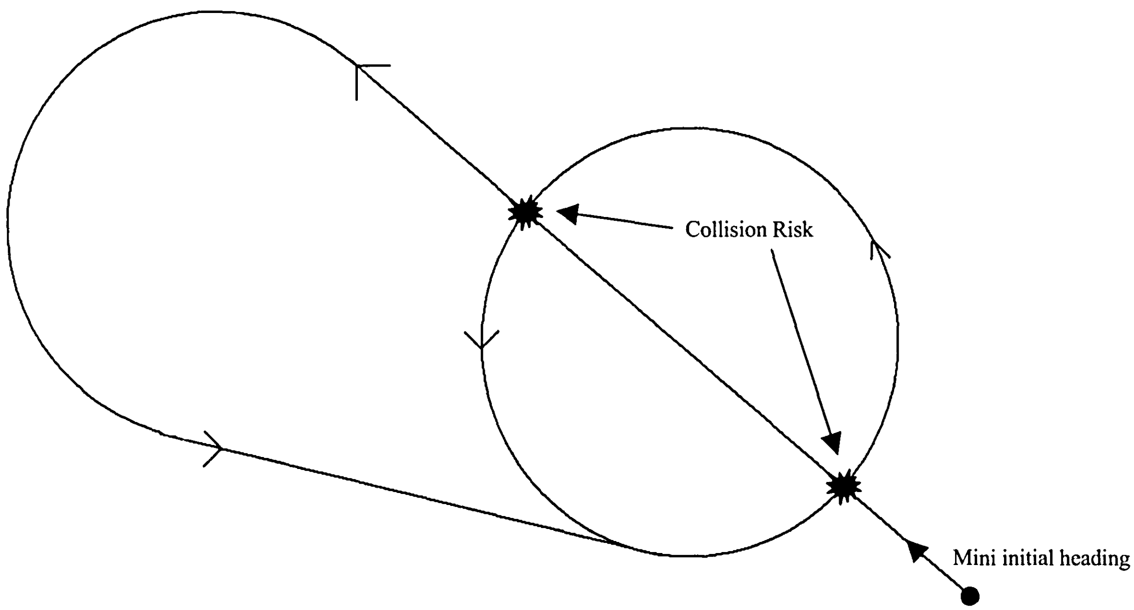


Figure 4.10 Initial configuration that leads to a possible collision

Consequently, a procedure must be implemented which will modify the path to prevent this crossing from occurring. Since L_1 is the synchronization parameter, any heading correction must be done before this step otherwise the synchronization will be lost. Therefore, if a crossing occurs when the Mini initially computes its path, the trajectory must be altered. This modification can be done in a couple of different ways. The Mini can keep flying straight below the Parent altitude, and by updating the computed trajectory, proceed with Phase I whenever the crossing does not happen anymore. Another strategy would be for the Mini to change its heading by engaging into a turn. In either case, the Mini does not proceed with the initial computed trajectory.

This collision avoidance strategy has not been implemented for demonstration because of the added complexity. Also, since the team on the ground monitors the aircraft, it can intervene if a collision risk arises.

4.7 Objective System Strategy

The material about Phase I that has been covered so far dealt with demonstration. This section describes the modifications necessary for an objective system.

Since R/C airplanes are used for demonstration, the aircraft must always remain in the pilot's sight, so that the safety pilot can take control in case of some kind of malfunction during these demonstrations. This implies that the vehicles must remain within about 500m from the pilot. However, in the objective system the Mini and the Parent will fly at very different altitudes (several kilometers). Therefore, a slightly different strategy for Phase I is suggested for an objective PCUAV system.

As described in 4.4.2, during the demonstration of Phase I, the Mini climbs in a straight line at an angle of $6°$. In the objective system, the altitude difference is initially large, and if the Mini climbs along a straight line, it will have to fly several kilometers in the horizontal plane in order to reach the desired altitude. For example, an initial altitude difference of 1000m would require the Mini to fly more than 9500m in the horizontal plane to reach the Parent level. At this point the two aircraft would be far apart from each other and Phase I would be time-consuming and very inefficient.

As a consequence, in the objective system the climb could be reshaped into a helix. This would guarantee that the Mini stays in the surveillance area and within communication range of the Parent.

Moreover, since in this configuration the flight time during the climb will be great, the synchronization between Mini and Parent can be achieved only by choosing the velocity of the Mini. This did not work in the demonstration strategy as discussed in 4.3.2, because in certain cases the Mini was too close to the Parent circle initially, so that the required velocity was too high or too low. Now if the Mini is well below the Parent, this situation will not occur and the vehicles can be synchronized without having to perform L_1. Therefore, for the objective PCUAV system, Phase I is composed of:

- a *helical climb*;
- a *turn*;
- a *straight line*.

Figure 4.11 illustrates such a long range trajectory computed using MATLAB.

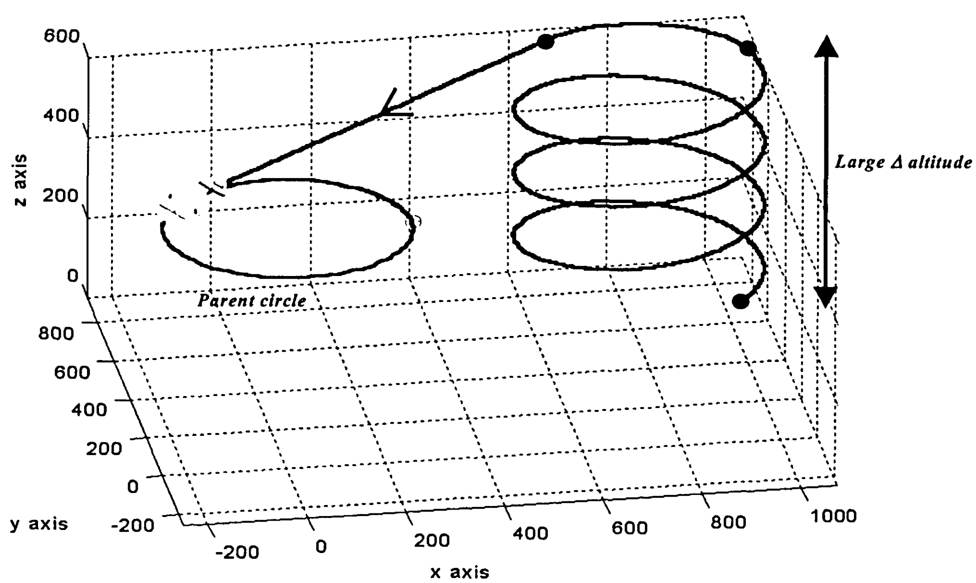


Figure 4.11 Objective system trajectory with a helical climb

4.8 Chapter Summary

The requirements and constraints for designing a trajectory for Phase I were presented in this chapter. These criteria were used to design a trajectory using elementary geometric blocks. It was then discussed how a straight line called L_1 could be used in order to bring the Mini 15m behind the Parent at the end of Phase I. Finally, it was shown how to modify the trajectory for an objective system.

Chapter 5

Guidance along the Trajectory

5.1 Chapter Overview

Chapter 4 described the shape of the Phase I trajectory and how to construct it. This chapter focuses on the guidance of the Mini along that path. First, an XYZ time constrained guidance strategy will be explored, then Proportional Navigation (PN) will be discussed, and in light of flight tests results, it will be explained why the latter strategy was chosen. References will be made to MATLAB Simulink and to the hardware-in-the-loop simulation. More details about these tools can be found in Appendix B.

5.2 Time Constrained XYZ Control

5.2.1 The Phase II Guidance System

First, the guidance for Phase II designed by Sanghyuk Park in 2001 [1] is explained. In this phase, the Mini navigates relatively to the Parent, that is, the frame of reference for the coordinates of the Mini is moving with respect to inertial space. The frame of reference for the Mini navigation is centered on the target located on top of the Parent and the axes are the body axes of the Parent. The Mini calculates its coordinates in this frame using the optical sensor discussed in Chapter 3. These coordinates represent the distances that the

Mini needs to correct in the three axes directions (hence the name XYZ guidance) in order to reach the Parent: the forward, sideway and vertical differences. The control system of Phase II is designed to zero out these values. For more details about the actual control system please refer to [1] and [2].

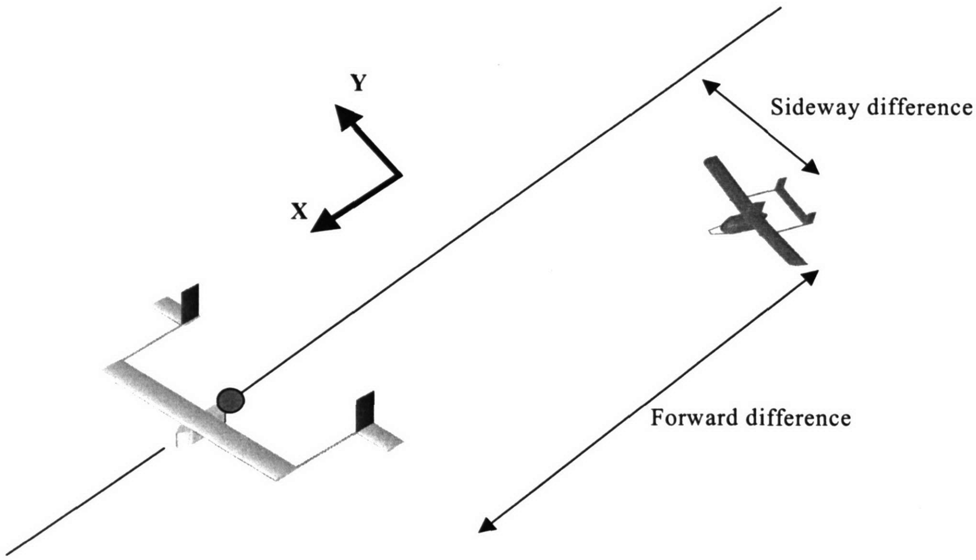


Figure 5.1 Phase II XYZ control

5.2.2 Application to Phase I

Since this guidance system, along with appropriate controllers, was available before any Phase I work had begun, it was decided to use the same guidance and controllers for Phase I and Phase II. Such a strategy offered a lot of advantages since it made use of previous work and did not require any major guidance transition between Phase I and Phase II.

A few modifications needed to be made in order to adapt the XYZ guidance to Phase I. First, one difference between Phase I and Phase II is that during Phase I the Mini would not follow an actual aircraft like the Parent; instead a reference point would move along the designated path at the required velocity and be the center of a referential for the Mini.

Three axes would be linked to this moving point and they would serve as the frame of reference for the Mini navigation. The reference point moves along the path at a constant velocity so that at any time its position is known. Using its position information and its onboard clock, the Mini is then able to calculate at any time what its forward, sideways and vertical difference is relative to the reference point. This strategy was therefore named XYZ time-constrained guidance.

This guidance offers several advantages. Previously mentioned is the fact that the control system was already designed and would remain the same during both reintegration phases. Second, the final synchronization of Parent and Mini is ensured since the reference point moves along the path at the velocity required for the final configuration. Provided the Mini follows this point correctly, the Mini is guaranteed to arrive in M_3 at the right time.

This guidance strategy was implemented and tested. Simulink simulations confirmed the validity of the method, since from any initial configuration, the Mini arrived 15m behind the Parent, thus fulfilling the Phase I objective. Under a constant wind of $8\,\mathrm{ms}^{-1}$ and gusts of $15\,\mathrm{ms}^{-1}$ for 3 seconds, the Mini still followed the reference point at the required velocity and achieved the Phase I synchronization. The hardware-in-the-loop simulation results were quite similar to those obtained with Simulink, although they showed more instability and sensitivity to initial conditions. For example, if the initial heading information used to compute the trajectory was not the exact real one (within a few degrees of error), the Mini sometimes diverged from the path and lost sight of the reference point. However, since the simulations worked fine most of the time, it was decided to test the system in flight.

5.2.3 Flight Test Results

This automated flight took place in July 2001. It was decided to test each controller seperately and for that purpose, different versions of the code were downloaded in the flight computer.

- For the lateral controller correcting the sideways difference, a straight line was generated. The aircraft controlled its ailerons and rudder to keep the desired alignment. The pilot still had control of the elevator and throttle.
- The vertical controller was tested by holding the current altitude and keeping a specific heading. In this test the pilot had no control over any control surface.
- If the above tests worked, it was decided that the forward controller would be tested when the whole Phase I was tested. At that time the Parent vehicle was not automated, so the Mini would perform a mock Phase I where the flight path of the Parent was simulated inside the Mini's computer.

Unfortunately, none of the above tests were successful. The airplane did not follow any of the specified trajectories, even the straight line. The team studied the data recorded during the autonomy attempts to determine the cause of the failure. When analyzing this flight data, it became obvious that there was an important inadequacy between the control system and the sensor's accuracy. In the following, the issues that came out of the flight test are discussed as well as how the team responded to them.

One of the most significant discoveries was that the GPS information used by the flight code had an embedded delay of about 10s. Richard Poutrel [6] modified the GPS system and the delay was reduced to an acceptable 300ms.

This GPS inaccuracy problem also led the team to reconsider the validity of using the same controllers for both Phase I and Phase II. Since the vehicle tries to keep up with a point in time and space, the XYZ control approach is very demanding in terms of accuracy. This was not a problem during the simulations since the position was known perfectly. Such a guidance is also relevant for Phase II because the position information provided by the optical sensor is fast and accurate. GPS, however, has an accuracy of only a few meters, as opposed to a few centimeters in the case of the Phase II sensor. This lack of accuracy is not compatible with a control system that was designed to correct centimetric deviations. It was decided that Phase I required the creation of a new control system.

The robustness of the guidance system was also questioned. In the event of a wind gust during Phase II, both vehicles are affected by it since they are close to each other. During Phase II the Mini navigates in a frame of reference linked to the Parent, so that if both vehicles positions are disturbed at the same time by a similar gust, the Mini relative position to the Parent will not be changed much. However, in Phase I, the reference point will not be affected by the wind conditions since it follows a fixed path referenced in absolute space. This means that the reference point will keep moving forward even when the Mini is deviated by a wind gust. The Mini control system is then required to correct large position differences, which it was not designed to do for Phase II in the first place.

These problems in GPS accuracy and robustness led the team to change the approach to guide the Mini on the trajectory. Thomas Jones suggested Proportional Navigation as a possible approach. Some of the advantages gained by using the same control system for Phase I and Phase II would be lost, but the following section will show the many other (and perhaps more important) advantages offered by Proportional Navigation.

5.3 Proportional Navigation

5.3.1 General Description

Proportional Navigation (PN) solves the problem of guiding a Chaser C towards a moving Target T. To simplify the discussion, only the two-dimensional problem will be considered in this sub-section. The 3D implementation is discussed in 5.3.2.1.

The line connecting Chaser and Target is called the Line Of Sight (LOS). It can be seen that if the LOS orientation is kept constant in inertial space, while its length decreases, the vehicles will collide, as shown on Figure 5.2. This is the principle used by PN.

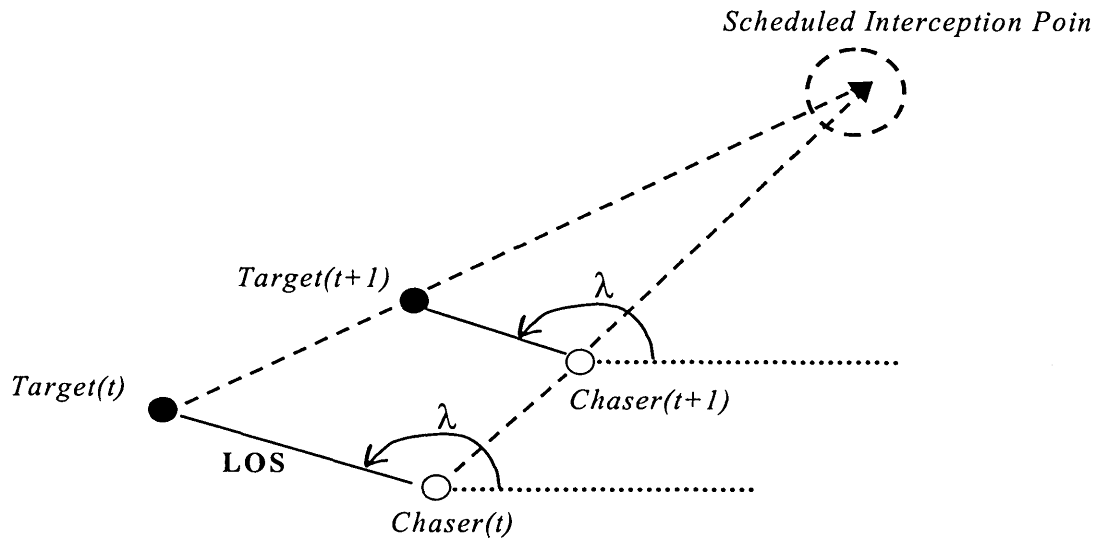


Figure 5.2 PN collision triangle

The goal of PN is to ensure that the LOS angle λ stays constant in inertial space, which is equivalent to keeping the LOS rate $\dot{\lambda}$ to zero. If the LOS is kept constant, the only requirement for collision is that the relative distance between Target and Chaser decreases. The 2D PN guidance law gives the following normal acceleration command:

$$N_c = NV_c\frac{d\lambda}{dt}$$

where N_c is the normal acceleration command for the Chaser, N is the *navigation constant* and V_c is the closing velocity of the Chaser with respect to the Target along the LOS. The navigation constant is usually between 2 and 5.

Practically, if the Chaser determines what the LOS rate is and applies the necessary acceleration command it will keep the LOS rate to zero and collision will occur. More details about PN can be found in [9] and [10].

5.3.2 Guiding the Mini with Proportional Navigation

Thomas Jones tried a direct implementation of PN for Phase I, with the Parent as the target and the Mini as the chaser. However, it was found that the trajectories generated were often non-optimal, requiring a lot of maneuvering, and sometimes there was no hit at all. Therefore, the team decided to keep the trajectory designed in Chapter 4 while using PN to guide the Mini on this path.

In order to guide the Mini on the path, an artificial point needs to be generated ahead of the Mini on the trajectory. This point is used as target, and by aiming at it the Mini will follow the specified path.

5.3.2.1 Modifications of the Model

A first difference with the model described in 5.3.1 is that the target point is stationary (although its position changes with time as discussed in the next section), therefore the closing velocity is simply the Mini velocity, and the PN guidance law becomes

$$N_{Mini} = NV_{Mini}\frac{d\lambda}{dt}$$

A second difference is that the problem is now three-dimensional. Two different accelerations must be given by the PN guidance law to guide the Mini toward the target point. Thomas Jones developed the model that is used by the Mini. Two planes are considered.

- First, the plane containing the North and altitude axis is considered. The vertical acceleration command is determined by calculating $\frac{d\lambda_{vertical}}{dt}$, the rate of change of λ in this plane, using the information of the Mini vehicle. This rate is then multiplied by the navigation constant N and the closing velocity V_{Mini}.

- Second, the horizontal plane is considered. Likewise, $\frac{d\lambda_{horizontal}}{dt}$ is calculated and multiplied by N and V_{Mini}.

These two acceleration commands are then fed into the control system to generate the required control surface deflections. Figure 5.3 shows a summary of the PN implementation in the Mini. Sanghyuk Park in [2] provides the reader with further details.

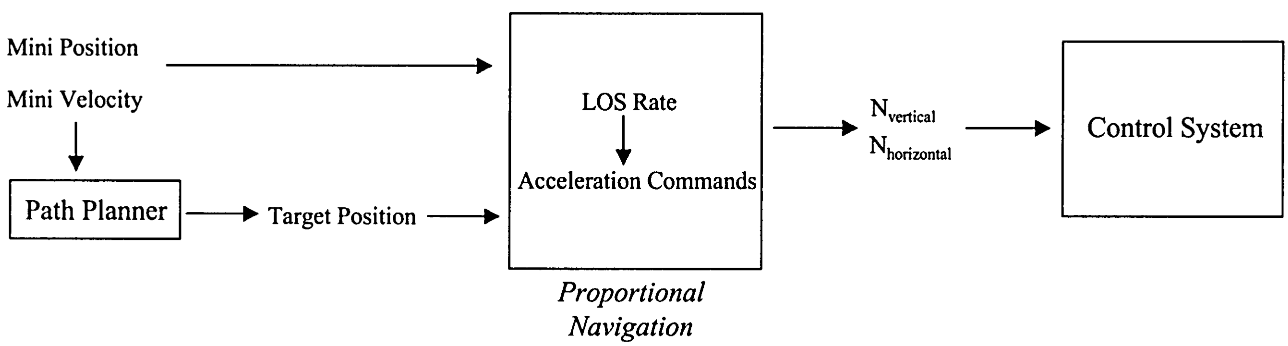


Figure 5.3 Summary of the PN guidance for Phase I

5.3.2.2 Target Point Location And Update

To use PN to guide the Mini during Phase I, two problems must be addressed.

- *Distance between Target and Mini*

The first problem is the distance X between the target point and the Mini. As will be demonstrated, this distance influences the quality of the tracking of the trajectory by the Mini. The Simulink model was used to choose the correct value of X. A circular trajectory was fed into the Simulink model and different values of X were used. The results are discussed below.

When the target point was too far away (several hundreds of meters), the Mini cut into the circle so that its actual trajectory is a circle with a smaller radius as shown in Figure 5.4. This is due to the fact that the Mini aims towards the target, so that the further ahead it is the more the Mini will tend to cut the circle.

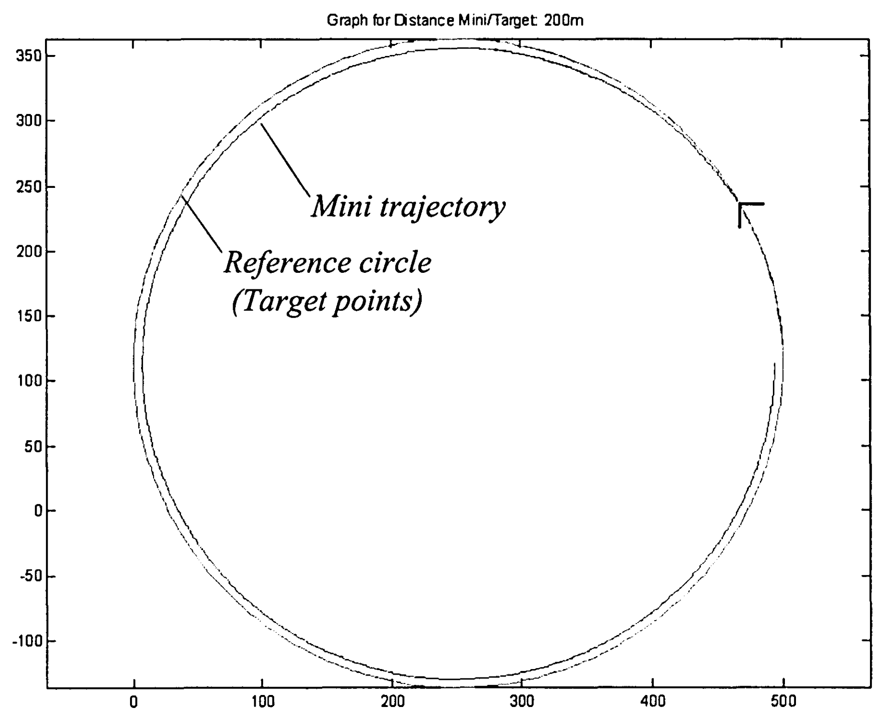


Figure 5.4 Deformed trajectory when the target point is too far (X=200m)

On the other hand, when the target point was chosen very close to the Mini (X=30 meters) the control system became unstable for the trajectory and the aileron command, as shown in Figure 5.5.

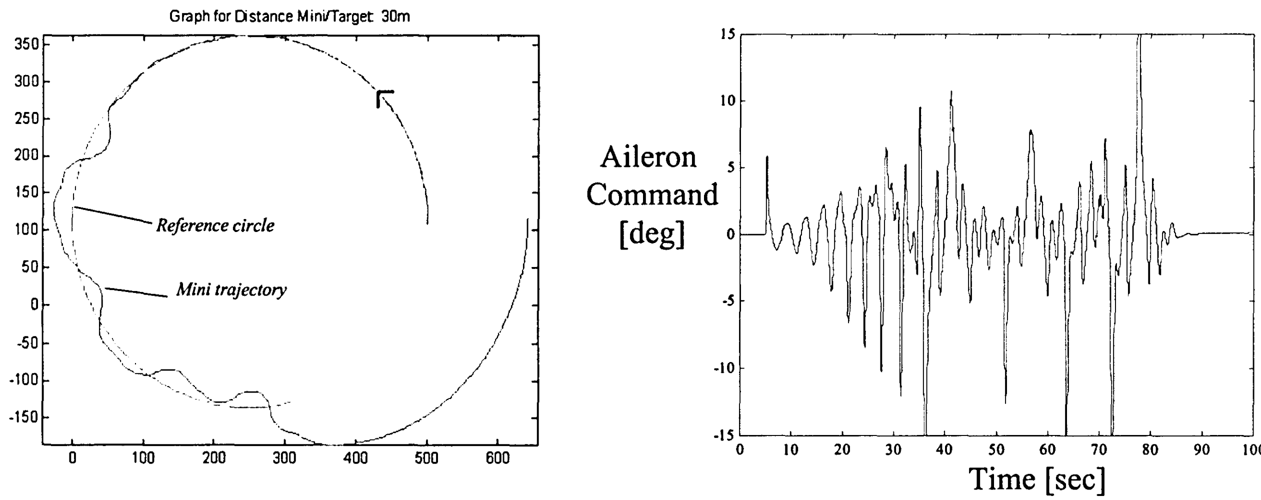


Figure 5.5 Navigation and aileron command instability when X=30m

This behavior is due to the proximity of the target point. As seen in 5.3.2.1, the control input is proportional to the LOS rate, which is in turn inversely proportional to the distance X so that the smaller X is, the larger the variations of the LOS rate will be. Therefore, the closer the aircraft is to the target, the larger the control corrections will be. As soon as the Mini deviates from the path, larger control commands are generated, leading the aircraft to become unstable and eventually diverge from the path.

A compromise has to be found between those two extremes, a distance that makes the control smooth without changing the shape of the desired flight path of the Mini too much. Thus, a distance of 100m was chosen which leads to a very smooth control of the aircraft while keeping the flight path fairly similar to the desired one, as shown in Figure 5.6.

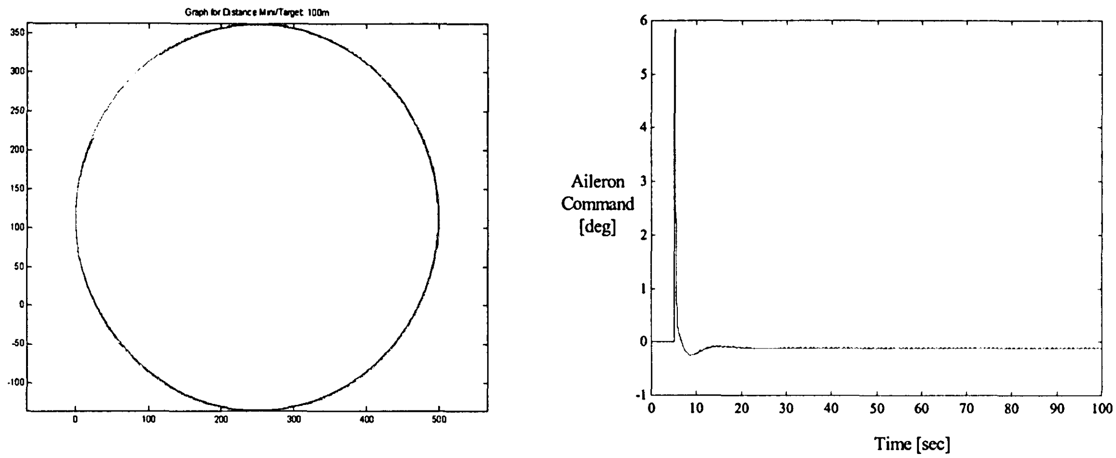


Figure 5.6 Trajectory and aileron command for X=100m

A more thorough discussion about the choice of this distance can be found in [2].

- *Update of the Target point location*

The second problem is the update of the target point position. The target point has to be periodically updated and placed further away on the path since the goal for the Mini is to follow the trajectory, not reach the artificial target point. Moreover, the distance between the target point and the Mini should be kept constant, equal to 100m, otherwise the unstability discussed above will arise.

The update of the target point is done in the following manner. Once the path is calculated, the coordinates of points belonging to the path and seperated by 5m are written in a file and indexed. Initially the Mini determines which point in this set is 100m away. Starting from index 0, which is the initial position of the Mini, the index is increased and the distance between the Mini and this point is calculated. The index is increased until the point is 100m ahead and this point is kept as target point. Since the GPS update rate is 5Hz it was decided to update the target point at the same rate. Therefore, 0.2s after having chosen its initial target point, the Mini calculates how far it is now from this point. If the point is still 100m or more away, then this point is kept as a target. But typically after 0.2s, the aircraft has gotten closer to the target so that the distance is smaller than 100m. The position of the Mini is then compared to points in the set that have a greater index. As soon as a point 100m ahead is found, it is used as the new target point and so on. Therefore, the Mini is always aiming at a point at least 100m away on the circle, which ensures good tracking of the path and a smooth and stable control.

5.3.3 Advantages of the PN Guidance

The advantages of Proportional Navigation guidance are twofold.

In the time constrained XYZ guidance described in 5.2, the target point was constantly moving forward and the Mini had to keep up with it. It was argued in 5.2.3 that such a system is not robust to withstand wind gusts, because as soon as the vehicle is off the path, it diverges. On the contrary if the Mini goes off course due to wind gusts, PN guidance will lead it back on the path. This guidance strategy is therefore more robust to external perturbations, especially to the wind which is a genuine concern during flight tests.

Moreover, the GPS information need not be very accurate. Indeed, what matters for the proportional navigation is the line of sight (LOS) to the target. Since the target is 100m away, a few meters of inaccuracy in the Mini position will not change the LOS angle by much. An inaccuracy of ΔL m in the position information will approximatly lead to a difference in LOS angle of:

$$\Delta\lambda = \frac{\Delta L}{100(1+\tan(\lambda)^2)}.$$

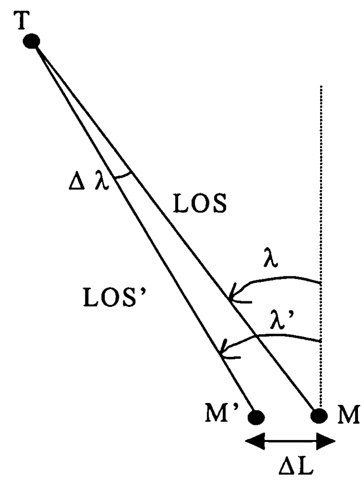


Figure 5.7 Effect of position inaccuracy on the LOS angle

For example, a ΔL of 5m leads to a maximum angular difference of $2.8°$ - which occurs when the LOS angle is $0°$. This difference is very small and can be handled well by the control system.

Therefore, a guidance strategy using PN resolves the robustness and GPS accuracy problems that the team faced during the July 2001 flight test.

5.4 Summary

This chapter described the evolution of the guidance strategy used for Phase I. An XYZ time-constrained guidance was first tried but then replaced by Proportional Navigation. This guidance strategy improves the robustness to withstand wind gusts and releases the constraint on meeting a high GPS accuracy requirement.

Proportional Navigation ensures an accurate and robust tracking of a given path. However, nothing was said about the synchronization and how to guarantee that the Mini would actually be 15m behind the Parent at the end of Phase I, a synchronization that was provided by the XYZ time constrained guidance. This point is the focus of the following chapter.

Chapter 6

Vehicle Synchronization

6.1 Chapter Overview

The previous chapter described the benefits of using proportional navigation to guide the Mini on its path. This guidance ensures good spatial tracking of the desired trajectory by the Mini but it does not put any constraint on how fast it should fly. This chapter deals with the synchronization between the Parent and the Mini in the context of proportional navigation.

First, the use of a ground speed controller will be discussed. Results from a flight test will then explain why the airspeed was taken into account and how this drove modifications of the planning system. Finally, results from a Phase I demonstration test are presented.

6.2 The Synchronization Problem

The Phase I trajectory discussed in Chapter 4 was built on the assumption that the Mini would fly at constant speed with respect to the absolute inertial frame. This was achieved by XYZ guidance but in the case of PN nothing constrains the length of time needed to complete the path. Therefore, the velocity of the aircraft has to be controlled in order to fly the trajectory at the required speed and by doing so, accomplish the final synchronization.

Sanghyuk Park created a ground speed controller and added it to the existing control system.

6.2.1 Simulations

The velocity controlled PN was tested for Phase I using Simulink. Some results are shown below in Figure 6.1.

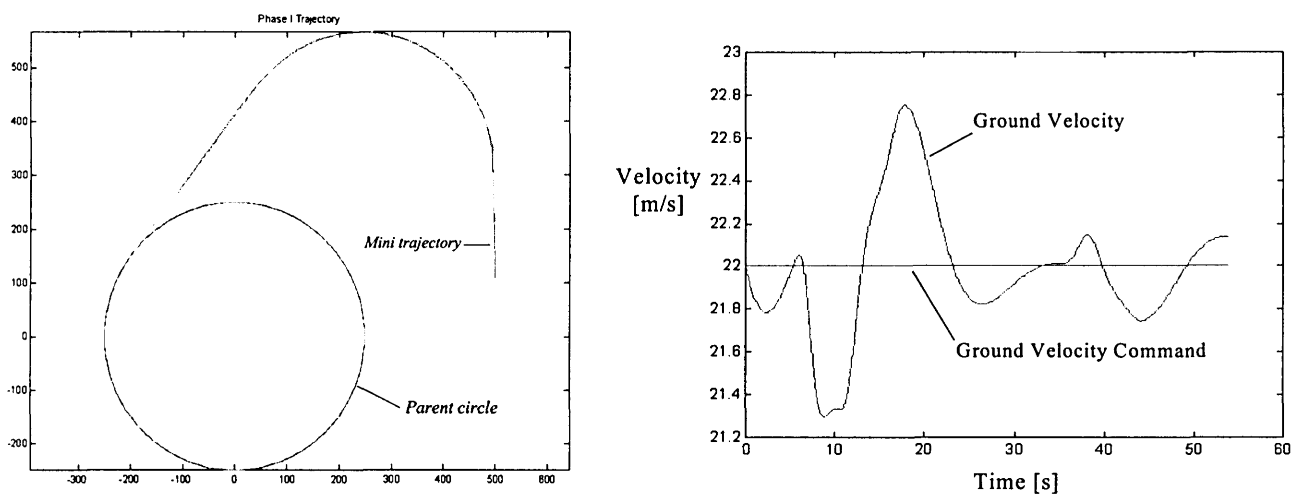


Figure 6.1 Results of a Phase I Simulink simulation using velocity controlled PN

It can be seen that the aircraft follows the trajectory correctly. The control commands are not jittery, and the ground velocity correctly tracks the constant velocity command set at 22m/s.

The hardware in the loop simulation was then performed, and again the results were very satisfactory. The path tracking was good and no instability was noticed. These simulations showed that the code was ready to be tested in flight.

6.2.2 Flight Test Results

The team devised a code version for a flight test designed to validate the control system of the Mini and assess its autonomy. The ATA was to fly along a circular pattern at a constant ground speed. This flight test was performed on November 1st 2001, and the ATA succesfully flew in a circular pattern using proportional navigation. This flight test was the first successful autonomous flight of a PCUAV aircraft and demonstrated the relevance of the changes discussed previously. The flight path of the ATA is shown on Figure 6.2.

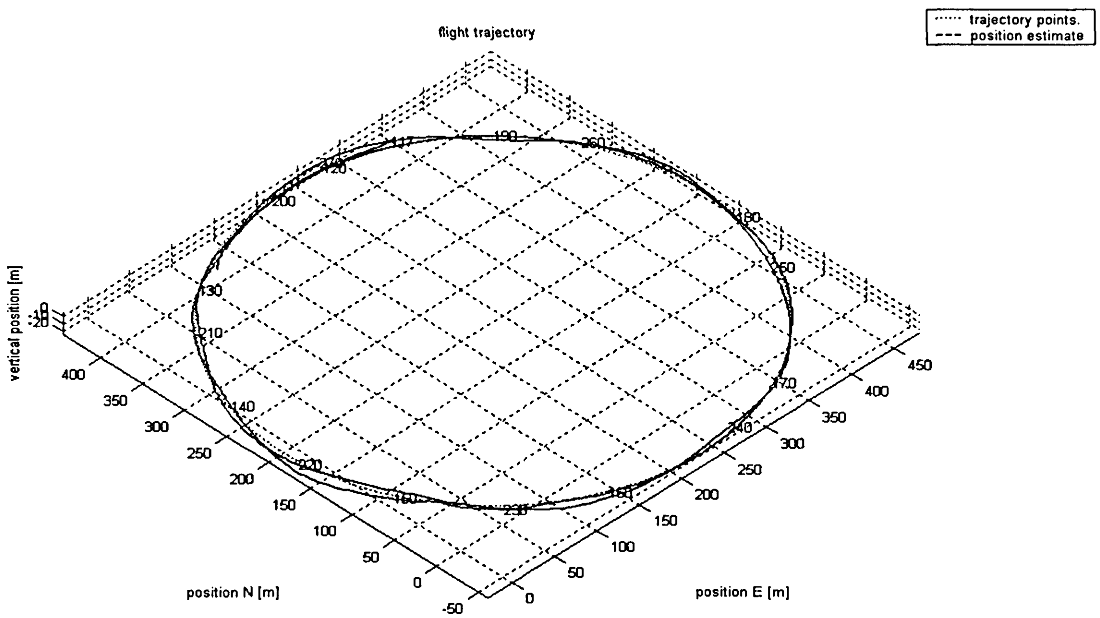


Figure 6.2 Nov. 1st 2002 - Flight Path

Unfortunately during the second autonomous flight the ATA stalled and after breaking its wing, came crashing into a nearby marsh. After two days of searching, the remains of the aircraft (and most importantly the flight computer) were retrieved. Fortunately, the computer was not damaged and the flight data was fully recovered. It should be noted that the use of an off-the-shelf R/C airplane like the ATA instead of the custom-built Mini for these software development tests was a wise idea.

It was found that this stall caused the aircraft to dive and that when the safety pilot took over and tried to recover it, the stress on the wing was too large, causing the wing to break. After analysis of the flight data, the reason for the stall was attributed to the ground velocity control. At the time of the stall, the ATA was flying downwind while trying to keep a constant groundspeed of 20ms^{-1}. This led the airspeed of the vehicle to drop below stall speed.

This flight test proved that the guidance strategy was good but it also clearly pointed at the need to take the airspeed into account. This concern drives the discussion of the remainder of the chapter.

6.3 Path Planner Modifications

The four step trajectory strategy detailed in Chapter 4 makes one assumption, namely that the Mini and the Parent fly their respective paths at a constant velocity relative to the absolute frame of reference, that is *with respect to the ground.* This assumption is necessary because in order to have final synchronization, future positions of the aircraft need to be estimated. If each of them flies at a constant ground speed along a known path, then this can be accurately predicted.

The November 1st flight test dramatically showed, however, that the aircraft should integrate the airspeed in their flight planning. The problem is that the wind is an unknown parameter and cannot be predicted. Therefore, if the aircraft navigate using only their airspeed, it is impossible to predict when each will get to M_3 and P_3 and there is no way to ensure the final synchronization. Some middle ground must be found that brings the aircraft 15m behind each other while ensuring that the airspeed does not drop below stall speed.

The speed controller needed to be modified to prevent stall. This is a major requirement to ensure survivability of the vehicle. It was decided that the aircraft should always try to keep up with the ground velocity command when possible, so that an approximate knowledge of future positions can be achieved. If during the flight, however, the airspeed reaches a lower bound (greater than stall speed), then this value becomes the command so that the aircraft never stalls. Therefore, the vehicles will not always fly at the ground velocity necessary to achieve synchronization. The planning system had to be revised to include such events.

6.3.1 Flexibility and Robustness Improvements

Previously the trajectory was calculated once and for all at the beginning, assuming a constant ground speed. Because the wind is introduced in the system, this open-loop strategy was no longer valid, and since the wind knowledge is not predictable, the only solution is to close the loop by updating the trajectory. Regular path updates take into account the current state of the vehicles so that synchronization is always ensured whatever the wind is. The update strategy depends on where the Mini is on the path:

a) During the climb and L_1, the remainder of the trajectory is updated at 5Hz and the ground velocity command is kept constant;

b) During the turn and the straight line, the trajectory is kept constant, whereas the velocity command changes at a 5Hz update rate.

In a) the synchronization is achieved by geometric update of the path through L_1. Before the turn the velocity command is constant, and the synchronization is done through the choice of L_1. By updating the value of L_1, the path is adapted to any disturbance that may have occured.

However, once the Mini enters the turn, there is no more geometric element to vary in order to change the arrival time at M_3, assuming a constant velocity; from the turn until the Parent circle, the path is fixed. Therefore, in this portion b) of the flight, the only available parameter to vary is the Mini velocity. Knowing the Parent position and assuming it keeps a constant ground velocity, the Mini determines what its ground speed should be for the remainder of the path in order to reach M_3 on time. The assumption made about the ground velocity of the Parent is reasonable because the Mini airspeed command is updated at 5Hz.

One problem with b) though is that synchronization is done through the choice of the ground speed. As was discussed at the beginning of this section, if the airspeed reaches a lower bound, then the ground velocity command is ignored, which jeopardizes synchronization. This risk was deemed worth taking mainly for two reasons.

First, part b) occurs at the end of Phase I so that the flight distances should not be large compared to the whole path, especially for demonstration. Therefore, if the velocity saturates, it should not affect the final synchronization too much. Most importantly, the Parent and the Mini will be subjected to similar wind conditions towards the end of Phase I since they will be close to each other and heading in the same direction. Therefore, by trying to fly at a ground velocity too low, both vehicles' airpeed command should saturate so that the saturations cancel each other out and synchronization is maintained.

The following paragraphs detail how these updates are done.

6.3.2 Trajectory Update

The trajectory is updated during the climb and L_1. The ground velocity command is a constant and is equal to the initial velocity of the Mini. As long as the Parent altitude is not reached, the whole trajectory is recomputed using exactly the same code as that used for the first calculation of the path. However, when the Mini reaches the required altitude, it does not include the climb phase in the trajectory calculation anymore, but starts the computation of the path directly with L_1.

Once the L_1 value is small, the Mini should not update the path anymore. Simulations showed that if the vehicle waited for L_1 to decrease below approximately 10m and kept updating its trajectory, then L_1 would suddenly increase by a large amount (typically between 500 and 700m), meaning this rendez-vous opportunity was missed and that the Parent has to make another full revolution for the next opportunity. This is the situation described in 4.5.2.

The threshold for transition between a) and b) was therefore set at $L_1 \leq 20\text{m}$ to prevent the Mini from missing the earliest rendezvous opportunity. From this instant until the end of Phase I, the path is fixed and the synchronization is achieved through the choice of the velocity.

6.3.3 Required Velocity Computation

6.3.3.1 Description of the Problem

Since the trajectory is fixed, so is the arrival point M_3 of the Mini on the Parent circle. The synchronization depends only on the timing of the arrival of the vehicles to this point. The velocity of the vehicles is what determines this timing, and therefore, at each time step a ground velocity command is generated that guarantees a good final timing. Knowing the positions of each vehicle and assuming a constant ground velocity for the Parent, it is easy to compute what the velocity of the Mini should be. This was implemented on Simulink and the synchronization was achieved. Figure 6.3 shows the good tracking of the path by the Mini and a good velocity tracking guaranteeing the final position synchronization.

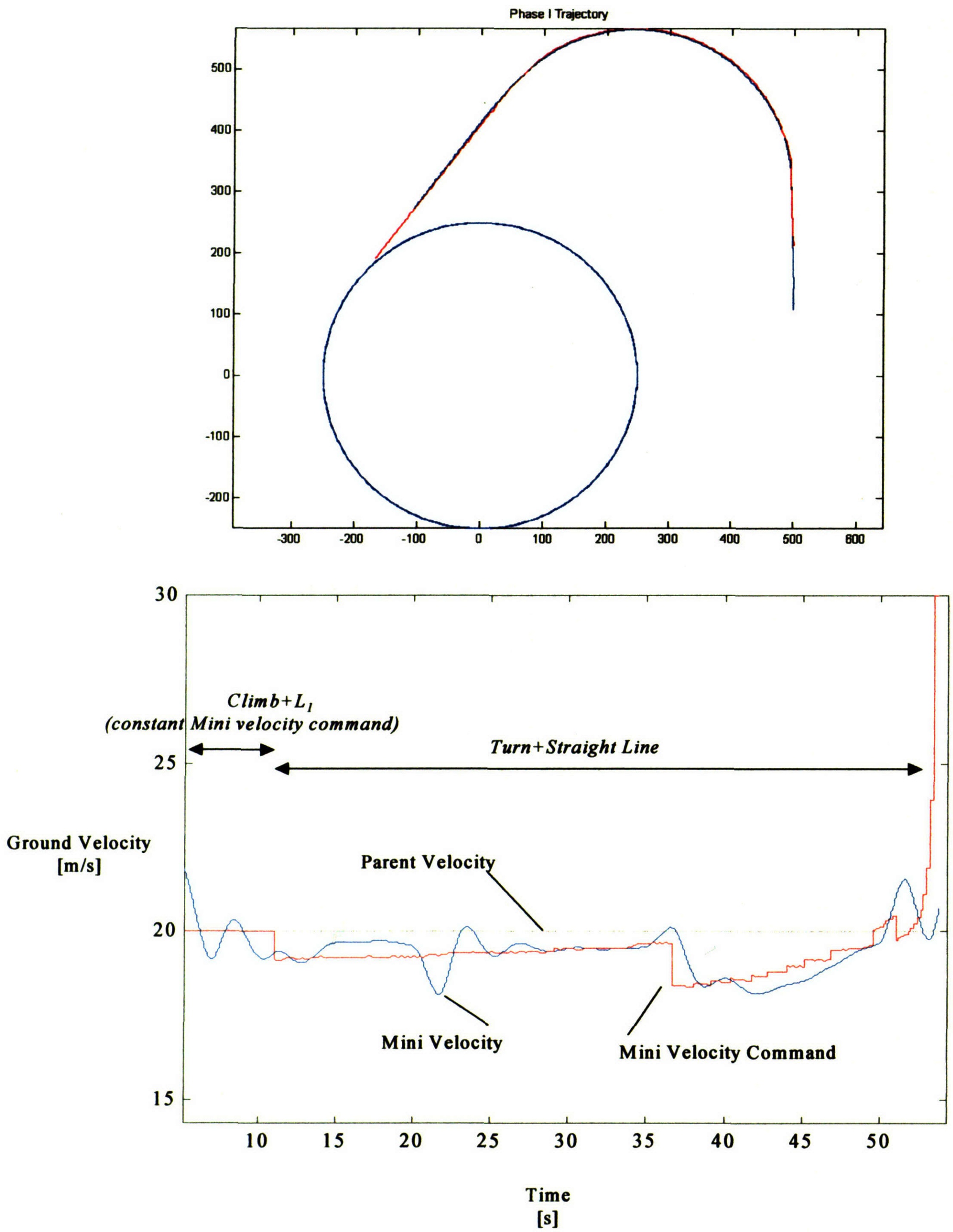


Figure 6.3 Graph showing the path (top) and velocity (bottom) of the Mini (Simulink)

However, this strategy overlooks one important variable. This algorithm only guarantees a final *spatial* configuration, but it does not specify anything about the *final relative velocity of the Mini with respect to the Parent.* This aspect is nevertheless crucial. For example, if the Mini arrives at M_3 with a velocity of 25ms^{-1} while the Parent flies at 20ms^{-1}, then a few seconds later there will be collision. The simulations confirmed this concern so that while the spatial synchronization was always successfully achieved, the relative velocity between the two aircraft was non-zero, especially when there was some wind.

Moreover, it can be seen in Figure 6.3 that after 50s, when the Mini gets close to M_3, the velocity command diverges. This is because the velocity is equal to the remaining distance to be flown divided by the remaining flight time (calculated from the Parent remaining flight time) as shown in (eq. 6.1).

$$V_{\text{Mini}_{\text{command}}} = \frac{\text{Distance(Mini, } M_3)}{\text{Time}} \qquad \textit{(eq. 6.1)}$$

$$\textit{where } \text{Time} = \frac{\text{Distance(Parent, } P_3)}{V_{\text{Parent}}}$$

At the end of Phase I, the Mini velocity command is more sensitive to variations of the remaining time, and simulations showed that the aircraft was always either accelerating or decelerating a lot so that even if the final velocities of the two vehicles matched, their accelerations were different and a collision risk was still present.

Consequently, the planner must determine the velocity that will ensure not only spatial synchronization but also velocity synchronization between the Parent and the Mini. The following describes the author's solution to this problem.

6.3.3.2 The Virtual Parent

As before, it is assumed that the Parent is passive and only tries to keep up with a constant ground velocity command while the Mini performs the active part of synchronization. This assumption can be released as described later in 6.3.3.4.

The solution chosen by the author is to create a *virtual Parent.* Since the trajectory is fixed, the position P_3 of the Parent at the end of Phase I is known. At any instant the distance between the Parent and P_3 can be calculated and is called L_{Parent}. Likewise the distance between the Mini and M_3 is known and called L_{Mini}. The idea is to place an image P* of the Parent on the Mini trajectory L_{Parent} meters from M_3. P* is also assigned the same velocity as the Parent. Figure 6.4 illustrates this concept.

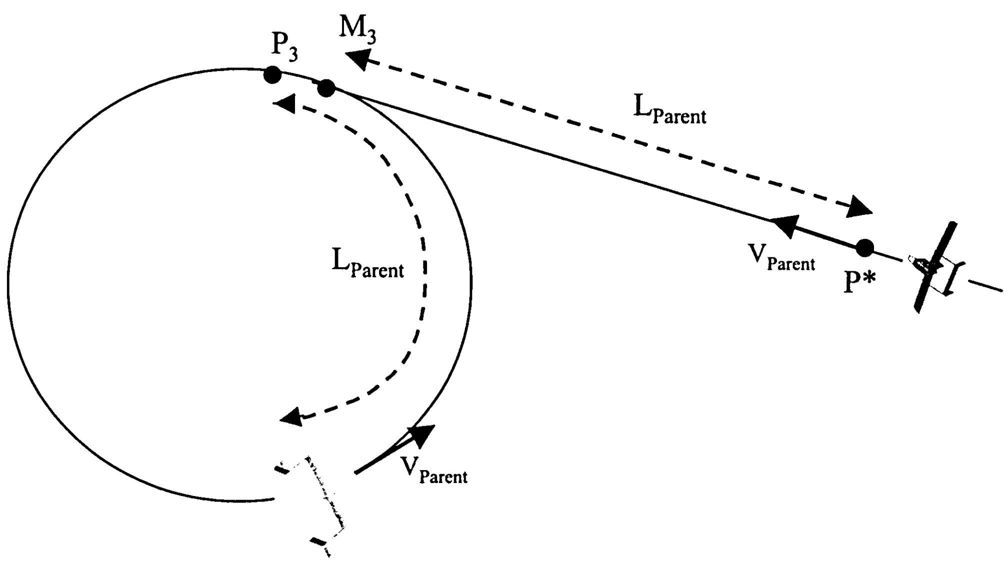


Figure 6.4 Virtual Parent on the Mini Trajectory

The goal for the Mini is to track P* through velocity control. If the Mini always keeps up with P* (which means that at all time $L_{Parent} = L_{Mini}$), the spatial and velocity synchronization will be achieved at the end of Phase I as described below.

1. **Spatial Synchrionization**: when $L_{Parent} = L_{Mini} = 0$ the Mini is at M_3 and the Parent in P_3 .
2. **Velocity Synchronization**: since the Mini always follows P*, which travels at the Parent's current speed, both vehicles have the same velocity. This is also true at the end of Phase I.

The positions and velocities of P* and of the Mini (M) are updated at 5Hz, so that the distance MP* between P* and M is available. This distance needs to be brought to zero in order to have final synchronization. Since before the turn the path was constantly optimized, the distance was initially zero, but wind gusts on the Mini *and* the Parent are likely to alter the synchronization as the Mini flies part b) of Phase I, so that MP* diverges from 0 if nothing is done. The goal of the next section is to determine how to control the velocity of the Mini so that MP* is always kept to zero.

6.3.3.3 Velocity Control

The control system of the vehicles is such that controlling the airspeed is much faster and more accurate than controlling the ground speed. For this reason, it was decided to control the airspeed of the Mini in order for the Mini to follow P*.

- *Velocity Synchronization*

In this section, only the velocity synchronization is considered so that MP* is assumed to be zero. The control law for the Mini is:

$$V_{air\ command\ (M)} = V_{air\ (P*)} \qquad (eq.\ 6.2)$$

The choice of the airspeed for P* must therefore be carefully made because it determines the final velocity synchronization. To ensure this synchronization at the end of Phase I, there must be:

$$V_{air\,(P^*)} = V_{air\,(P)} \textit{ at the end of Phase I} \qquad \text{(eq. 6.3)}$$

so that the airspeed of the Mini is the same as that of the Parent.

A possible choice for the airspeed of P* is to have it equal to that of the Parent at all times, ensuring the final condition of (eq. 6.3). However this is a problem for the position synchronization because Parent and Mini are subject to different headwinds as shown in Figure 6.5. In this figure, the Parent is keeping a constant ground velocity so that its airspeed is high. If the Mini tries to achieve the same airspeed by following P* while flying downwind, its ground velocity will be very high. This implies that if nothing was done for position synchronization, the velocities would be equal at the end of Phase I, but the Mini would not be where it should be.

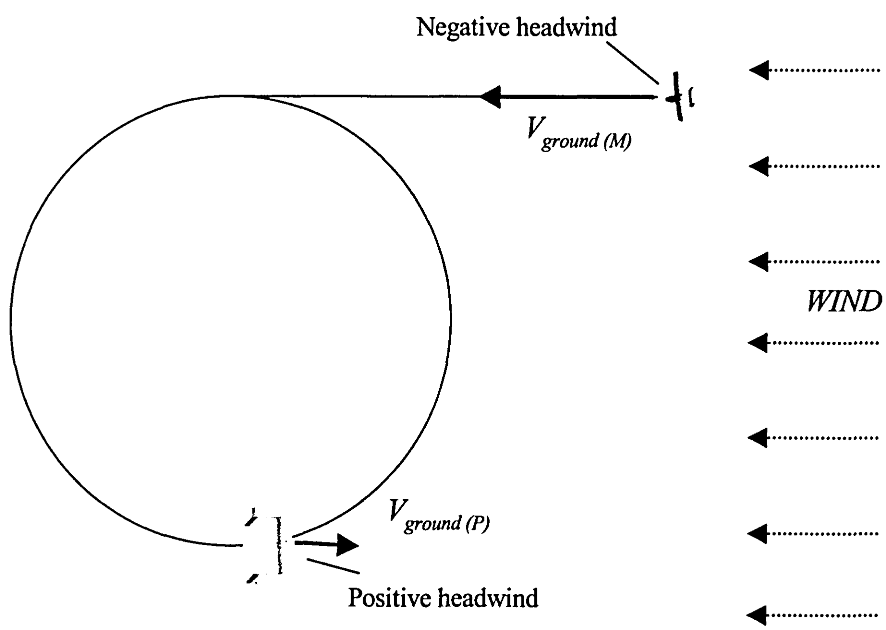


Figure 6.5 Influence of the headwind on the ground velocity

To prevent MP* from increasing a lot as was the case if $V_{air\,(P^*)} = V_{air\,(P)}$ at all times, the author chose to adapt the Parent ground velocity to the Mini's current wind conditions in order to assign a value to the velocity of P*. Indeed, the Parent has a certain ground velocity and another value for its airspeed depending on its headwind. The Mini has a different headwind and therefore, it will have a different airspeed for the same ground velocity. The value of the airspeed of P* was chosen to be the ground velocity of the Parent with the addition of the headwind of the Mini.

$$V_{air\,(P*)} = V_{ground\,(P)} + Headwind_{(M)} \qquad (eq.\ 6.4)$$

with $Headwind_{(M)} = V_{air\,(M)} - V_{ground\,(M)}$

When the Mini gets close to the Parent, both vehicles will be subject to the same wind so that the headwind of the Mini and that of the Parent will be equal and the airspeed of P and P* will be the same as shown in (eq. 6.5):

$$V_{air\ command\,(M)} = V_{air\,(P*)} = V_{ground\,(P)} + Headwind_{(P)} \qquad (eq.\ 6.5)$$

$$\ldots\ldots\ldots\ldots = V_{air\,(P)}$$

This guarantees that at the end of Phase I, the two aircraft will be flying at the same velocity.

• *Position Synchronization*

In the previous section it has been shown that if MP* is zero, the Parent and the Mini will have the same velocity at the end of Phase I. Moreover, an effort was made to keep the increase in MP* as small as possible by using an airspeed command for the Mini derived from the Parent ground velocity. The following control strategy drives MP* to zero to ensure the position synchronization.

As shown in Figure 6.6, if P* is ahead of M, then M needs to increase its velocity to cancel MP*.

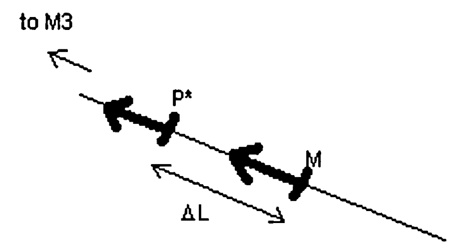


Figure 6.6 Mini lagging behind P*

Therefore, a second term must be added to (eq. 6.2) so that:

$$V_{air\ command\ (M)} = V_{air\ (P^*)} + \Delta_{vel}(MP^*) \qquad \textit{(eq. 6.6)}$$

where $\Delta_{vel}(MP^*)$ accounts for the change in velocity command due to a non-zero MP*. At first it was decided to simply use proportional control so that the Mini airspeed command is modified from the airspeed of P* by an amount Δ_{vel} directly proportional to MP*.

$$V_{air\ command\ (M)} = V_{air\ (P^*)} + K\, .\, MP^* \qquad \textit{(eq. 6.7)}$$

where K is a positive constant and MP* is positive when M is behind P*. Simulink simulations were performed and showed that a value of 0.8 should be chosen for K.

The results showed, however, that when the velocity control starts at the beginning of the turn, there is an initial non-zero value for MP*. This causes the throttle command to jump abruptly, which is undesirable for the hardware endurance.

To prevent this mode change it was decided to use a PI controller instead of proportional control. Δ_{vel} becomes:

$$\Delta_{vel} = K_1 \times MP^* + K_2 \times \int MP^* dt \qquad \textit{(eq. 6.8)}$$

The same results as with proportional control were obtained with values for K_1 and K_2 of respectively 0.5 and 0.01. If initially MP* is non-zero, it is possible to choose the initial value of $\int MP^*$ so that there is no jump in velocity command. For this to happen this initial value must be:

$$\int MP^*_{t=0} dt = -\frac{K_1}{K_2} \times MP^*_{t=0} \qquad \text{(eq. 6.9)}$$

$\int MP^*$ is then updated at 5Hz, which prevents mode changes to happen when the Mini enters the turn, and it ensures a smooth control.

The airspeed command generated is then fed into the airspeed controller created by Sanghyuk Park. This strategy provides the Mini with a robust synchronization logic that proved to work in simulations even under mild wind conditions.

6.3.3.4 A More Robust solution

The strategy described above performs well under mild wind conditions (up to 10m/s in simulations) and is satisfactory for the demonstration flights of PCUAV where the wind speed threshold was set to 5m/s. However, the objective system might be required to reintegrate when the wind conditions are stronger. This section will discuss a possible approach for more windy conditions.

The control system limits the range of airspeed from 18 to $30 ms^{-1}$. A problem occurs when the airspeed command of the Mini reaches the saturation level. If the headwind of the Mini is low, the Mini airspeed command can saturate, even for small values of MP*. This takes place, for example, when the aircraft is trying to correct a small negative value of MP* (the Mini is ahead of P*) and is flying downwind. In this case the airspeed command of the Mini can saturate at $18 ms^{-1}$, whereas the required value for synchronization would be lower. Therefore, the synchronization cannot be guaranteed anymore.

In all the previous discussions, it was assumed that the Parent was totally passive. It is now necessary to release this constraint and allow the Parent to have a dynamic velocity control. The main idea is as follows.

- Due to the wind conditions and the value of MP*, the Mini required airspeed command is 18 - V_{excess}. However the Mini flies at 18ms^{-1} to prevent stalling.

- So far the Parent was keeping a constant ground velocity command. The idea is to give the Parent the excess velocity V_{excess} as a command. If it was flying at 22ms^{-1}, it just needs to speed up of V_{excess}. This compensates for the fact that the Mini was not able to fly slowly enough, and the synchronizaion is maintained.

- As soon as the airspeed command of the Mini increases above 18ms^{-1}, the Parent comes back to a constant ground velocity command and becomes passive again.

This is summarized in Figure 6.7 for the airspeeds. $V_{Minimum}$ is 18m/s and $V_{required}$ is the velocity at which the Mini must fly in order to maintain the synchronization. The velocity command to the Parent is initially constant.

This has not been implemented in the PCUAV system but requires a minimum amount of work since everything is ready for it. The Parent already receives the airspeed command of the Mini, and therefore the Parent code can be modified to take it into account. Another strategy quite different from the one described above can be envisioned to solve this problem with significant wind. It is presented in Appendix C.

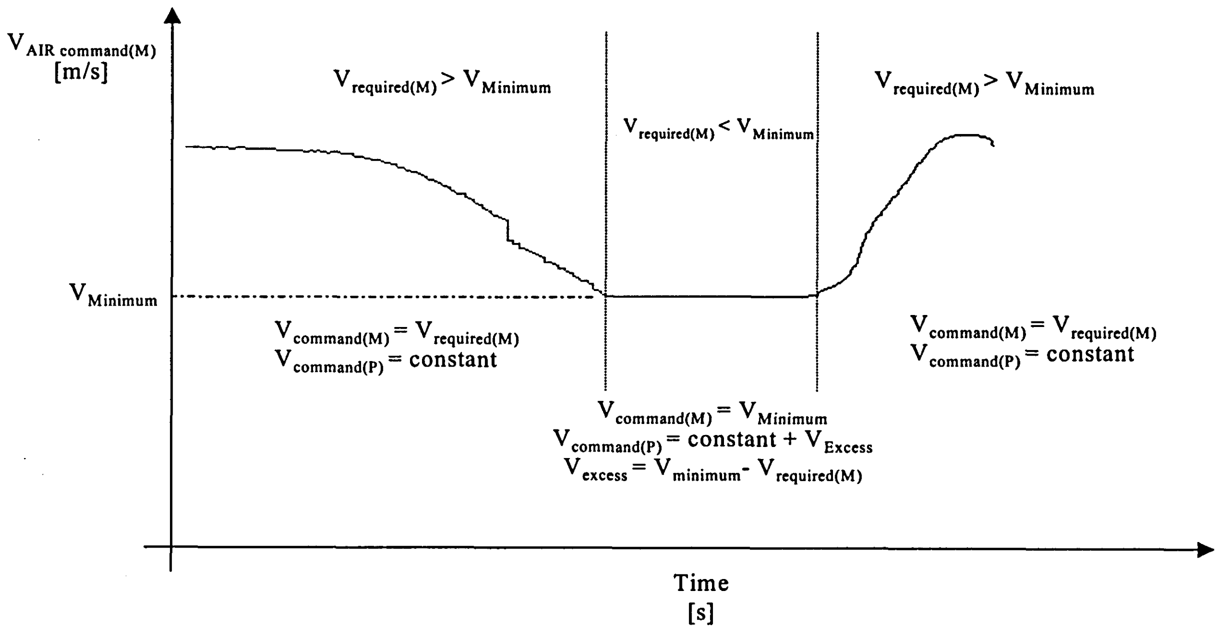


Figure 6.7 Active control of the Parent velocity

6.4 Phase I Flight Test

6.4.1 Flight Test Logistics

It was decided for the first flight tests to try Phase I for a final distance greater than 15m, in order to avoid collisions in case the synchronization strategy did not work as planned. A final distance of 30m was chosen, but once Mini and Parent were in formation flight on the Parent circle, this separation distance could be brought down by a ground operator.

This flight test requires a lot of logistic effort because two airplanes are in the sky simultaneously and careful attention must be given to each of them. The numerous tasks to be performed during the test were therefore broken down between the team members so that the load on each person might be minimized. The crew needed for Phase I is:

- *One pilot for the Parent.* He takes off the Parent R/C and lands it. He must be ready to take back control of the airplane at any time during the autonomous flight in the event of an autopilot failure;
- *A copilot for the Parent.* He turns on the Parent computer and engages the autopilot from a remote control. Since the pilot is busy and must stay focused on the aircraft, it was decided to give him a single interlocutor who would filter the relevant information from the rest of the team that the pilot must know and help him make a decision in case of problem. The copilot provides such an interface;
- *A pilot for the Mini* (same as above);
- *A copilot for the Mini* (same as above);
- *Two persons at the Ground Station laptop.* Before the autopilot is turned on in each airplane, they check via a wireless modem if all the onboard sensors are working well and they give clearance for turning on the autopilot. During the autonomous flight they monitor the status of each vehicle and give updates to the rest of the team. They must be able to detect any malfunction and warn the pilots to take over. Because of the multitude of tasks involved when two vehicles are in the air, it was decided to put two persons at the Ground Station. The display of information on the Ground Station laptop was also made as graphical as possible to make the data more readable and to display alerts. A picture of the laptop is shown on Figure 6.8 and a further description of it can be found in Appendix D.

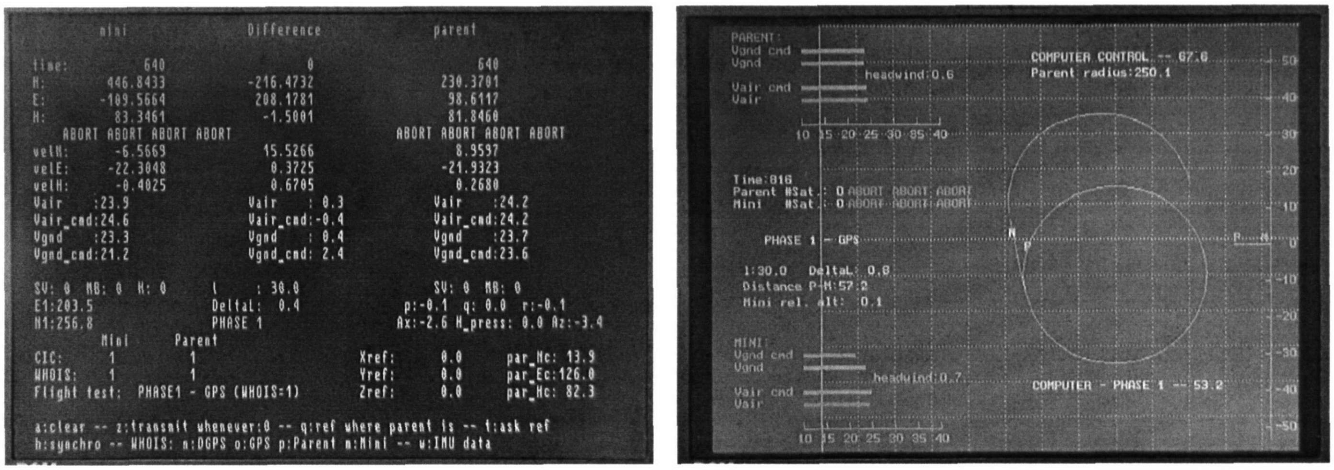


Figure 6.8 Ground Station display: no graphics (left), graphic interface (right)

- *One person filming the flights*. It ensures that the team has visual data from the flight which can be helpful when some malfunctions are observed.

These tasks are summarized in Figure 6.9.

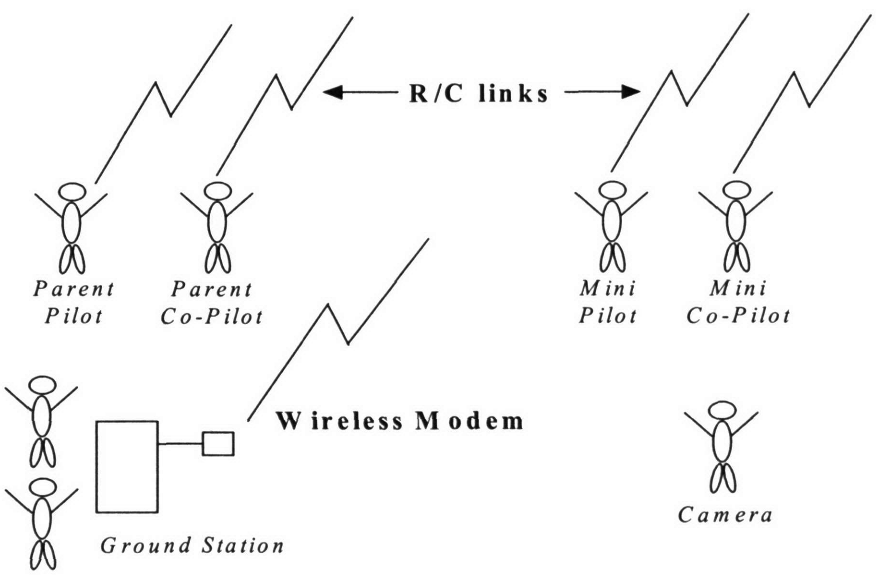


Figure 6.9 The crew required for Phase I

Once the crew is in place the sequence of events is the following.

- **Parent**
  - The Parent pilot takes off the Parent R/C;
  - The Parent computer is started and the Ground Station checks that all the onboard sensors are functionning correctly.
  - When the Parent is at a satisfactory altitude, the Parent copilot engages the autopilot which makes the Parent circle autonomously. The Ground Station keeps monitoring the autonomous flight and warns the pilot of any problem.
- **Mini**
  - When the Parent is autonomous the Mini pilot takes the Mini off;
  - The Mini computer is turned on and the onboard sensors are checked by the Ground Station.
  - Before the Mini autopilot is turned on to perform Phase I, the Ground Station displays what the trajectory would be. This is to prevent large trajectories where the Mini pilot would lose sight of the aircraft. Once the Phase I path is small the Ground Station lets the Mini copilot know.
  - The Mini copilot engages the Phase I autopilot and the Ground Station monitors the status of the aircraft.
  - At the end of Phase I, the Mini is 30m behind the Parent, flying on the Parent circle. The Mini copilot reduces the separation distance until the Mini is 15m behind the Parent.

6.4.2 The Phase I Demonstration Test

On July 19, 2002, the first full demonstration of Phase I was attempted and succeeded at Shirley, MA. The following week on July 25 the test was repeated after a few modifications were made to the altitude controller and it was again a success. The flight paths of the vehicles during one of the the July 25 tests is shown on Figure 6.11, with the positions of the vehicles displayed for different times during Phase I. The shape of the trajectory is the one described in Chapter 4 and the Mini arrives on the circle right behind the Parent.

Figure 6.10 shows the airspeed control of the Mini, with the airspeed command variations in order to ensure final synchronization.

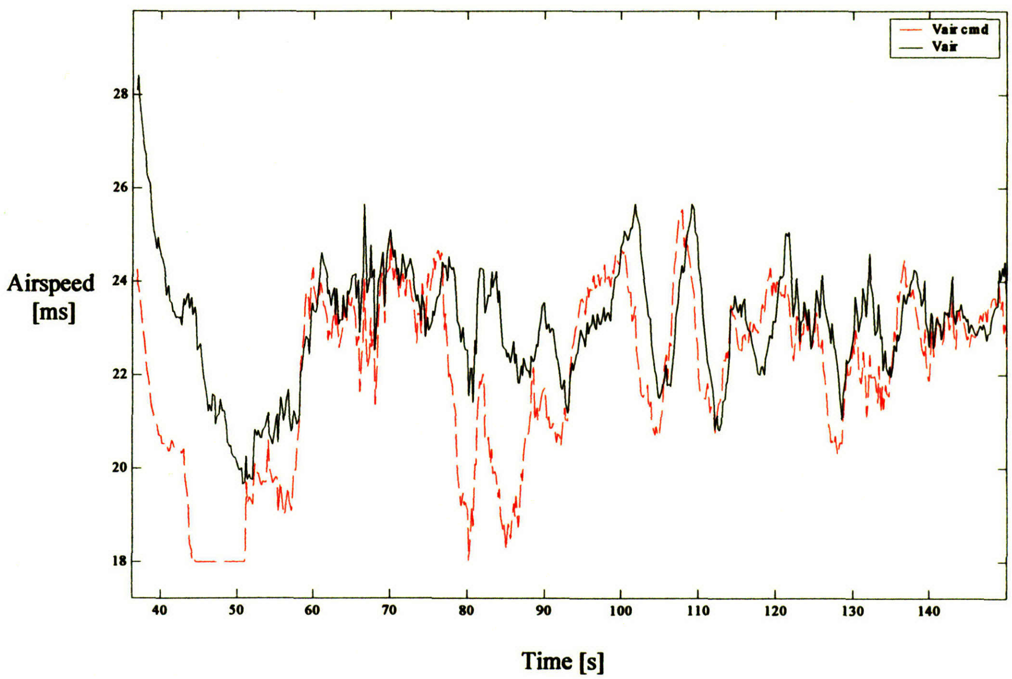


Figure 6.10 Mini airspeed command (dashed) and airspeed (plain) (July 25th 2002)

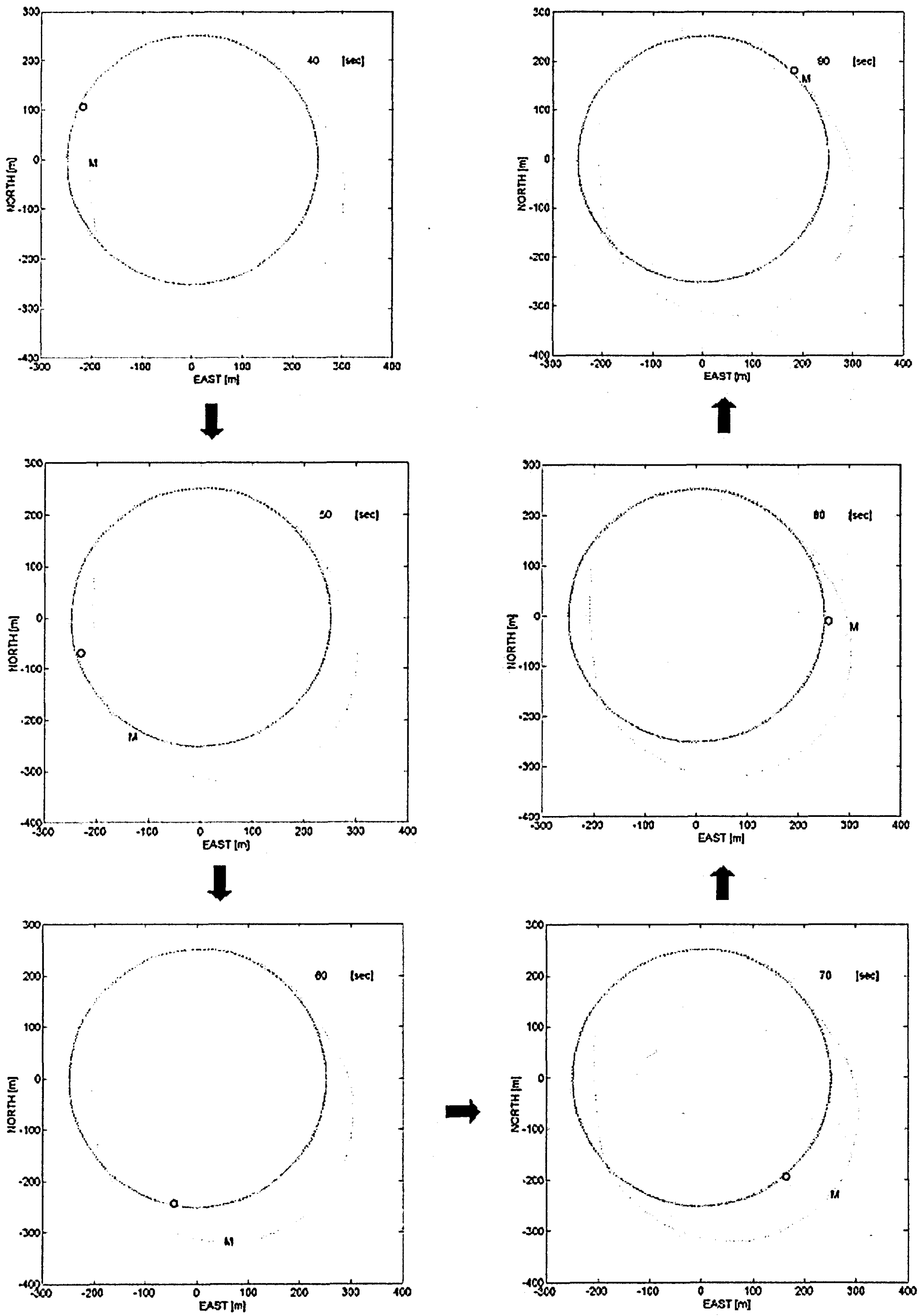


Figure 6.11 Flight trajectory with positions of Parent (O) and Mini (M) at 10s intervals (July 25th 2002)

The command for the final distance between the Parent and the Mini was set at 30m. Figure 6.12 shows a plot of the horizontal difference between the two aircraft. The peaks are due to communication loss and do not reflect real discontinuities. It can be seen that when the Mini arrives on the Parent circle it overshoots of about 6m, before settling at the required separation distance of 30m. The overshoot is due to the residual relative velocity between the aircraft, but is small enough to prevent collision. If the separation distance had been set at 15m, the Mini would have remained between 10 to 20m behind the Parent. This fulfills the goal of Phase I since the Mini is safely (i.e. without collision risk) brought close enough to the Parent for Phase II (and its the optical system) to take over.

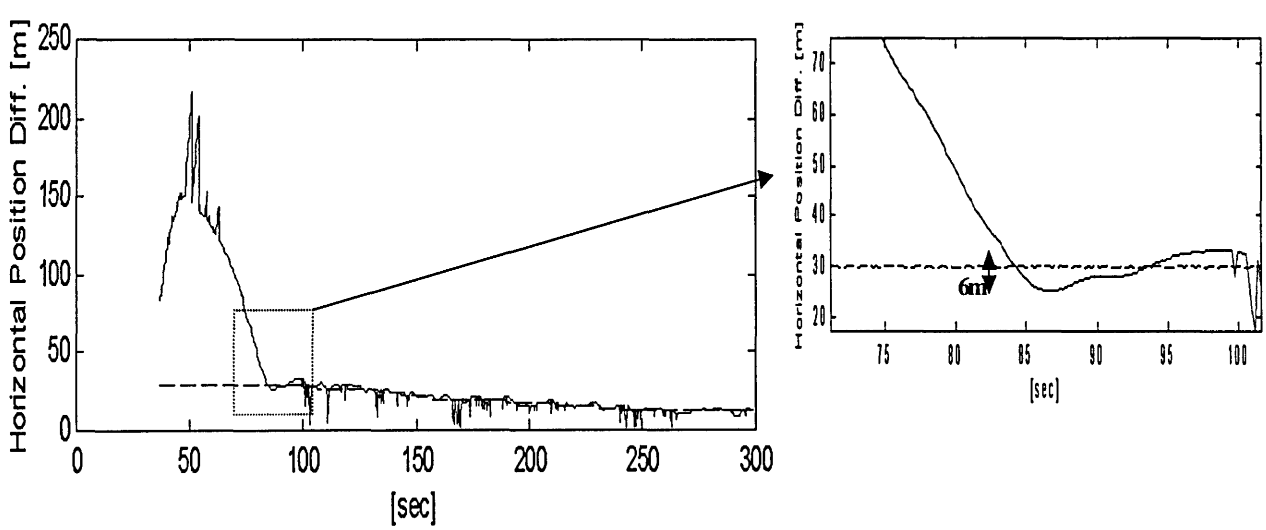


Figure 6.12 Horizontal position difference between Mini and Parent (July 25th 2002)

More flight data and pictures can be found in Appendix D.

The next step for PCUAV is to demonstrate Phase II. As of December 2002, the weather was not allowing the team to go and perform the test, although the hardware and the software are ready.

6.5 Chapter Summary

This chapter presented how velocity control ensured the synchronization of the vehicles. It was first shown that the airspeed needed to be taken into account to prevent a stall of the aircraft. Then the synchronization model was modified to account for the wind - an unknown parameter - and to provide final position and velocity synchronization. Finally, the flight test results of July 2002 were presented to demonstrate the relevance of the strategy.

Chapter 7

Thesis Conclusion

This thesis presented the path design, navigation and synchronization used in PCUAV for the Phase I of reintegration. The core of the thesis is the Path Planner which ensures that the Mini is 15m behind the Parent at the end of Phase I. The following diagram summarizes the way the Mini Path Planner is integrated within the Mini software.

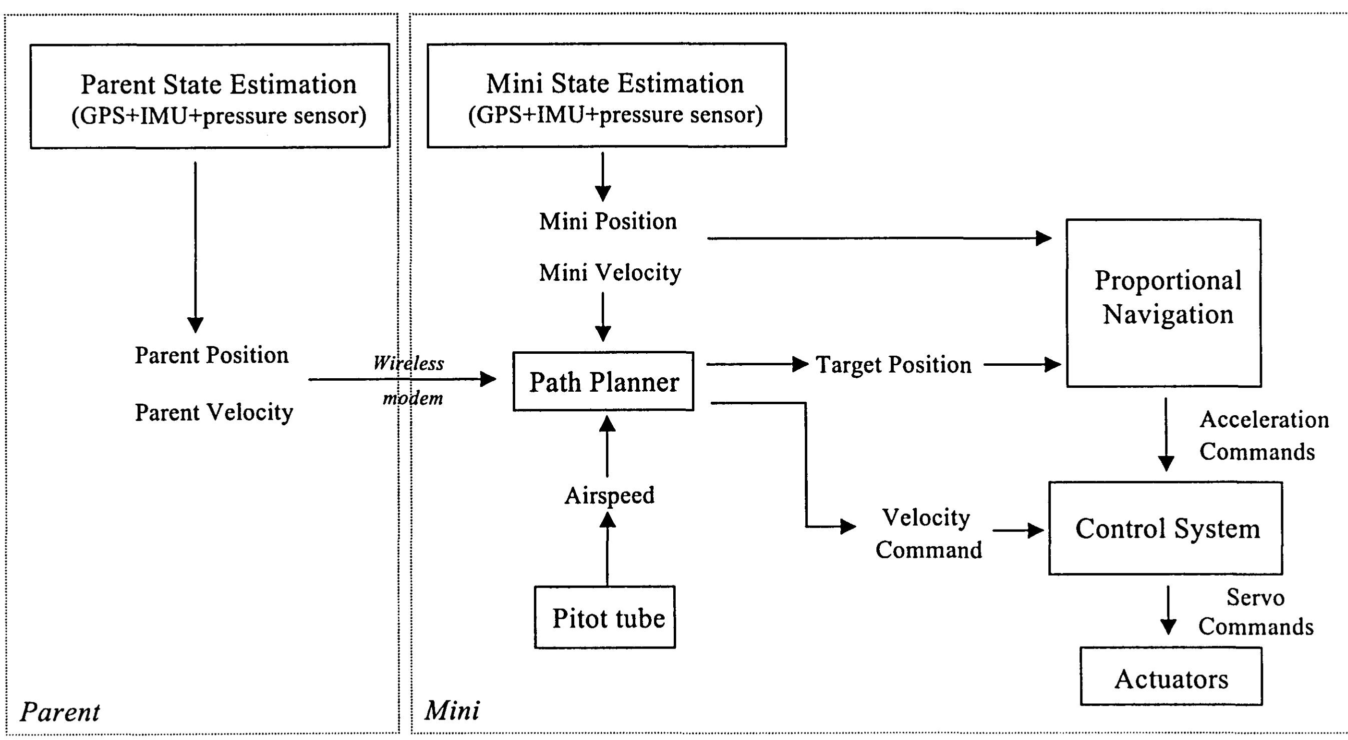


Figure 7.1 Path Planner inputs and outputs

The Path Planner inputs are:

- The Mini position and velocity derived from an estimator using GPS, IMU and pressure sensor information;
- The Parent position and velocity via a wireless modem;
- The Mini airspeed from the Pitot tube, used for the synchronization.

Using these inputs the Path Planner generates the following outputs:

- A Target point 100m ahead on the path. It enables the Mini to accurately follow the trajectory (spatial tracking);
- A velocity command, which ensures the synchronization between Mini and Parent at the end of Phase I (temporal tracking).

The Target point coordinates are fed into the Proportional Navigation block that generates two acceleration commands in order to guide the Mini. These commands are used by the control system to give deflection commands to the servos. The velocity command is used in the control system to fly the Mini at the required speed.

The strategy chosen was tested in flight and proved to be robust and effective. There are many possible techniques that could be used to compute PCUAV paths, and the approach chosen here is not optimal in terms of duration. However, it meets the needs of the PCUAV test environment and systematically provides the desired configuration at the end. Furthermore, the path could be updated at 5Hz because of the very small computation time required. Other algorithms that might be used to solve this kind of problem are usually computationaly expensive and are often not guaranteed to converge. The four elementary trajectory blocks used here provide the aircraft with a robust way to perform synchronization and reliably position the Mini within the range of the optical system in order to perform Phase II.

The next step for PCUAV would be to demonstrate Phase II, which will hopefully happen in the Spring of 2003.

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Appendix A

Examples of Phase I Paths

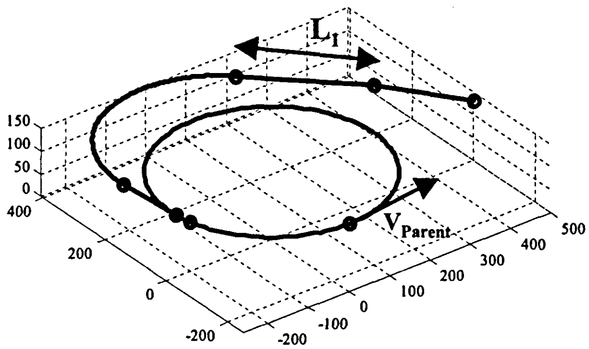
The following figure displays different Phase I trajectories using MATLAB, where the initial position of the Parent is varied. Since the Parent flies on a circle, knowing its initial position is equivalent to knowing its initial heading. The initial heading of the Parent (measured from the East axis) is indicated under each figure. The intial state of the Mini is:

- Position: East = 500m, North = 0m, Altitude = 130m
- Heading = 3*pi/4 (135 degrees)

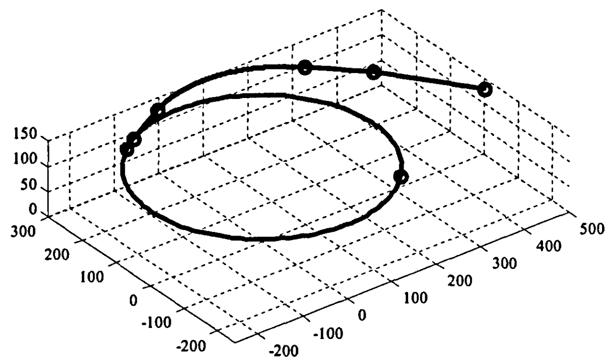
The vehicles velocities are set at 20m/s.

On every figure the Parent circle is displayed at the same position. The Mini path always starts from the same location, but L_1 influences the shape of the trajectory. These figures show the dependance of L_1 on the initial conditions and displays how the trajectories can be different for a constant Mini state.

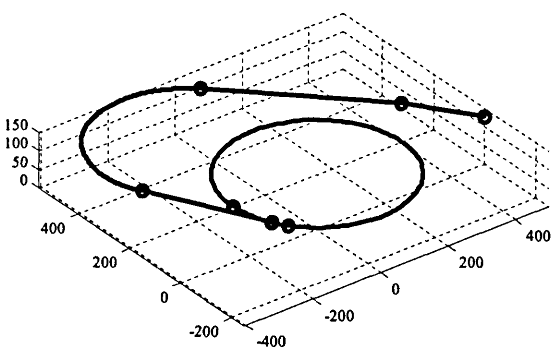
The waypoints described in Chapter 4 are also displayed, as well as the initial position of the Parent on its circle.



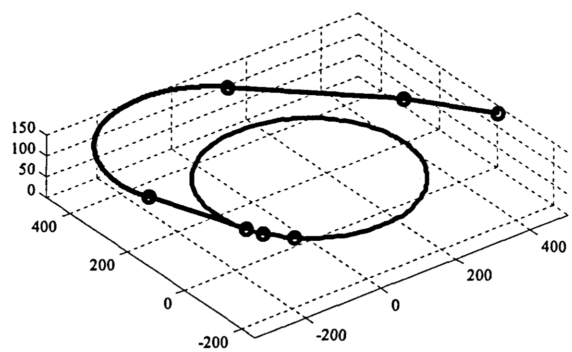
ψ_{Parent}=0



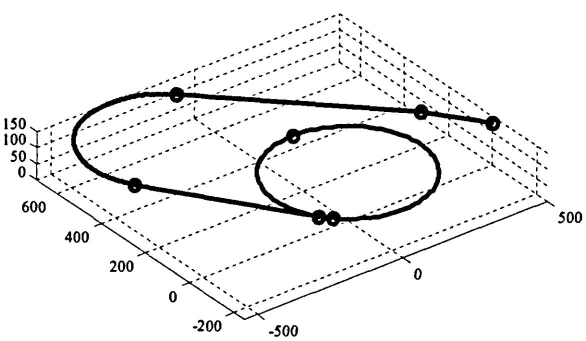
ψ_{Parent}=pi/4



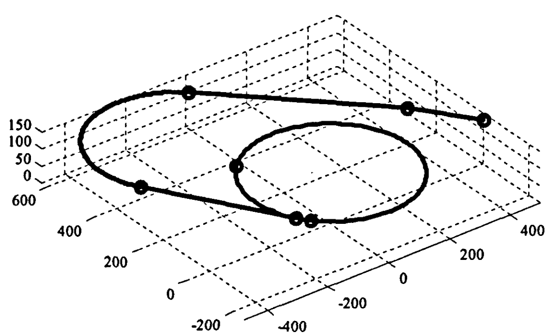
ψ_{Parent}=-pi/2



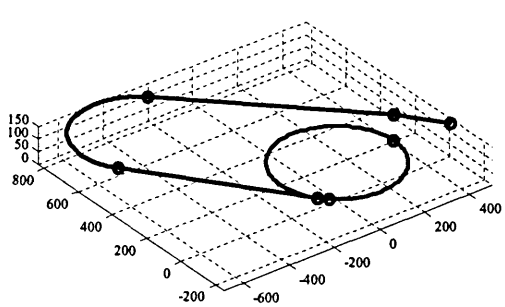
ψ_{Parent}=-pi/4



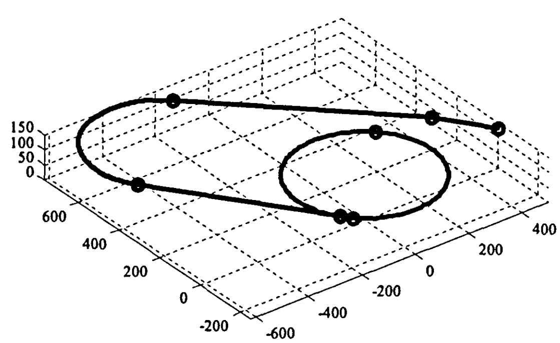
ψ_{Parent}=pi



ψ_{Parent}=-3*pi4

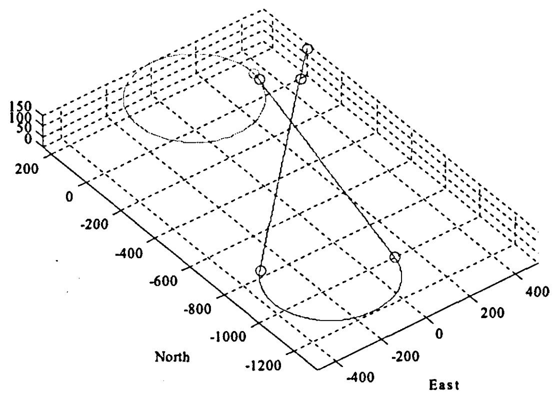


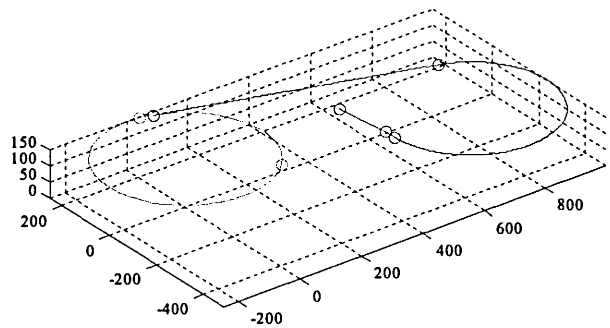
ψ_{Parent}=pi/2

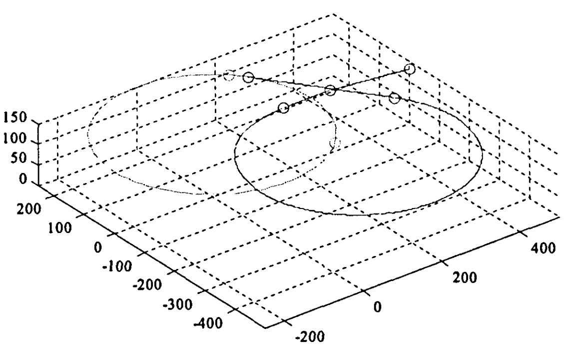


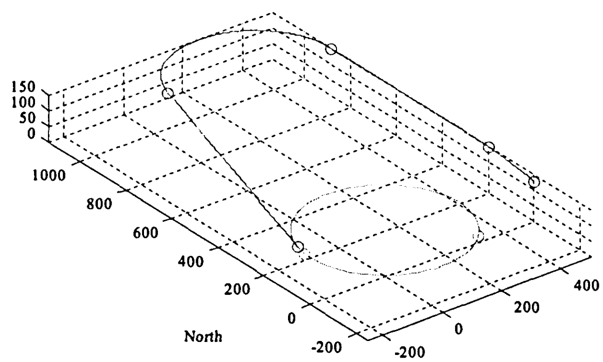
ψ_{Parent}=3*pi/4

The following figures show different shapes of Phase I paths for different initial Mini heading values, where this time the Parent intial position remains constant.









Appendix B

Simulation Tools

B.1 The Simulink Model

Sanghyuk Park [1] created a simulator using MATLAB Simulink. Figure B.1 shows the top level architecture of the model.

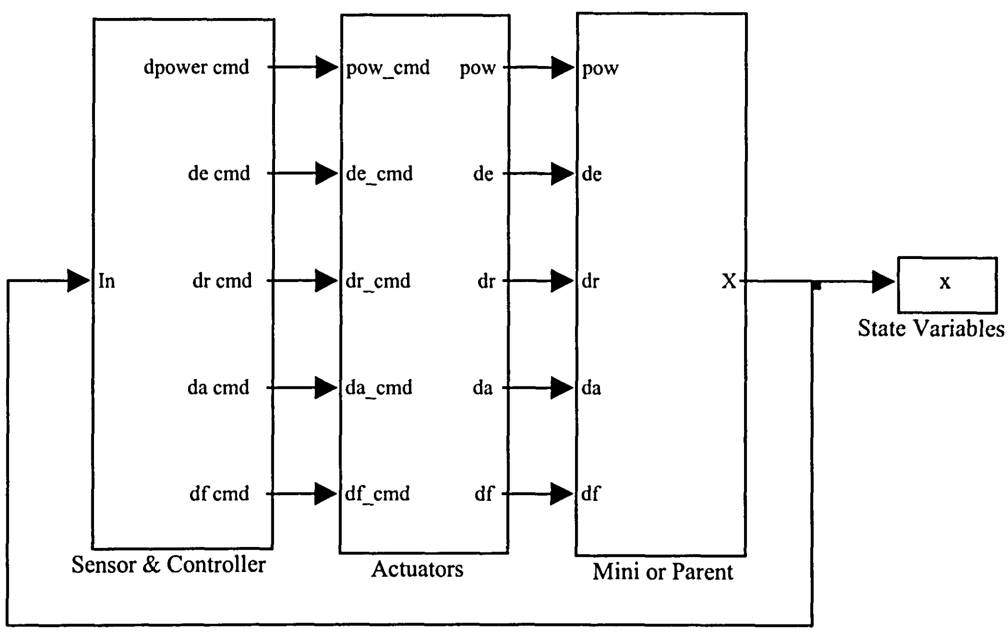


Figure B.1 Top-level View of the Simulink Model

The state variables are:

- The position (3 states);
- The velocity (3 states);
- The attitude angles pitch, roll and yaw (3 states);
- The angular rates of these angles.

The three blocks are briefly described below.

Mini or Parent (vehicle dynamics):

The dynamics of the vehicle are modeled in this block. The inputs are the states of the control surfaces - elevator, rudder, ailerons and flaperons - and engine setting. Using this information, the model determines the state variables of the vehicle X. This modelization of aircraft dynamics was done by Sanghyuk Park using [11].

Sensors and Controllers:

The input comes from the output of the dynamics block. However, since the onboard sensors only measure a few of the vehicle state variables, only the position, roll rate and bank angle of the vehicle are known. The controllers generate the servo commands.

Actuators:

These commands are fed into the next block modeling the actuators. The output describes the updated state of the control deflection and engine setting.

The sensor and controller block is where the proportional navigation logic is implemented. The Path Planner uses the vehicle position, velocity, and heading angle to generate the target position and velocity command. Using this information, Thomas Jones constructed the blocks generating the acceleration commands, which are then transformed into velocity, flight path angle, roll rate and bank angle commands.

This simulation enabled the validation of the guidance law and the target point generation along the path. The model also included a wind model that can create gusty wind conditions thus, providing more realistic conditions.

B.2 The Hardware in the Loop Simulation

In the Simulink simulation, a single PC models nature (the aircraft dynamics), the aircraft computer, and the aircraft actuators. This is useful during the development phase of the flight code in order to debug it and test whether it fulfills its goals or not.

During the flight tests, however, the code runs on a PC104 stack and sends commands from its serial ports to the servos via SBC2000. The stack also receives input via the serial ports from the GPS receiver and the wireless modem and via its data board. The hardware in the loop simulation aims at incorporating these components into a simulation in order to make the environment around which the code runs more real. Figure B.2 illustrates the parts involved in this simulation.

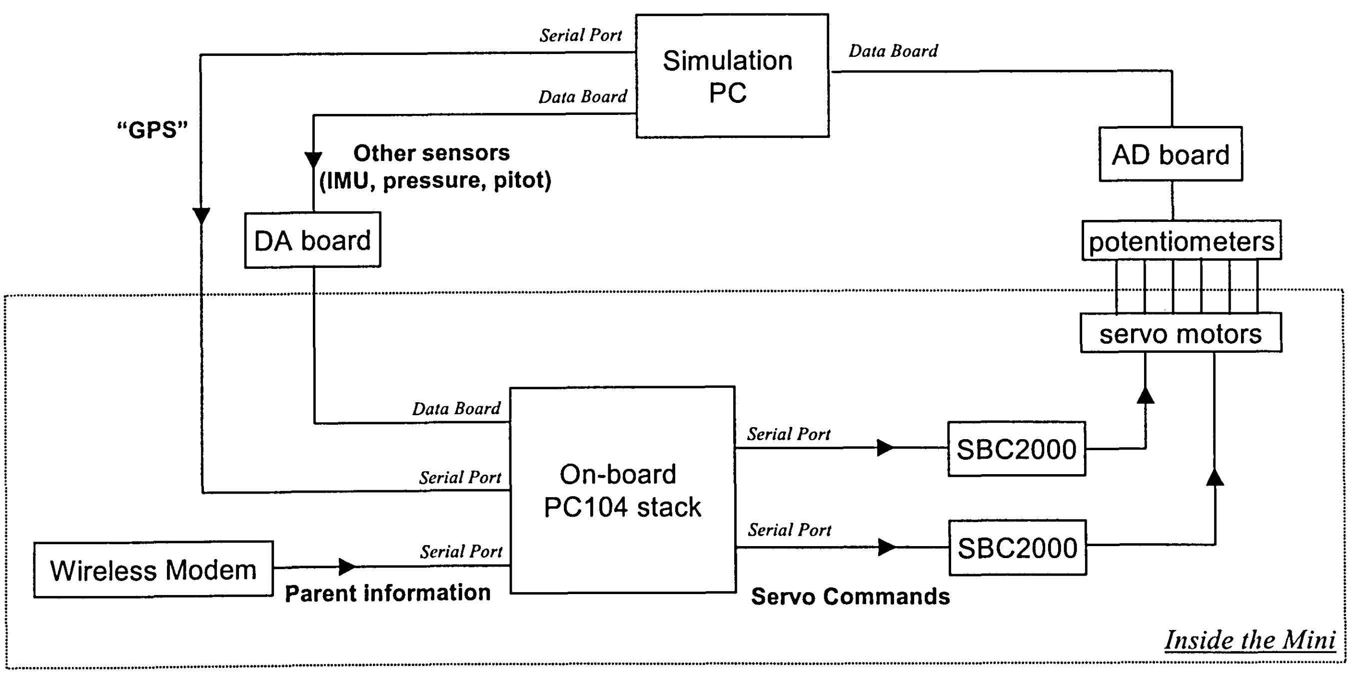


Figure B.2 Hardware in the Loop Simulation Diagram for the Mini

The flight code is run in a PC104 similar to the one used in flights. It gets input from:

- A Simulation PC for the Mini state. The position and velocity information is transmitted via a PC104 Serial Port (as is the case in flight for the GPS receiver) while the rest of the sensor information (IMU, pressure sensor, pitot tube) goes through the data board.
- A wireless modem for the Parent infomation. The Parent information is generated on another computer.

The PC104 output are servo commands. They are sent to the servos via two SBC2000 serving three servos each.

This reproduces exactly the I/O environment in the aircraft during flight. The aircraft dynamics are still to be modeled. For this purpose, the servos deflections are read using six potentiometers. The Simulation PC runs a flight simulator and takes these deflections as inputs and computes the current state of the aircraft. These states are then transmitted to the Mini as described above, closing the loop.

Figure B.3 shows a picture of the implementation of the simulation in the PCUAV lab. These simulations were very useful when integrating the path planner code, the control code and the communication code together. It helped debug the flight code and validate its performance in a realistic environment.

For more information about the hardware in the loop simulation, please refer to [1] and [2].

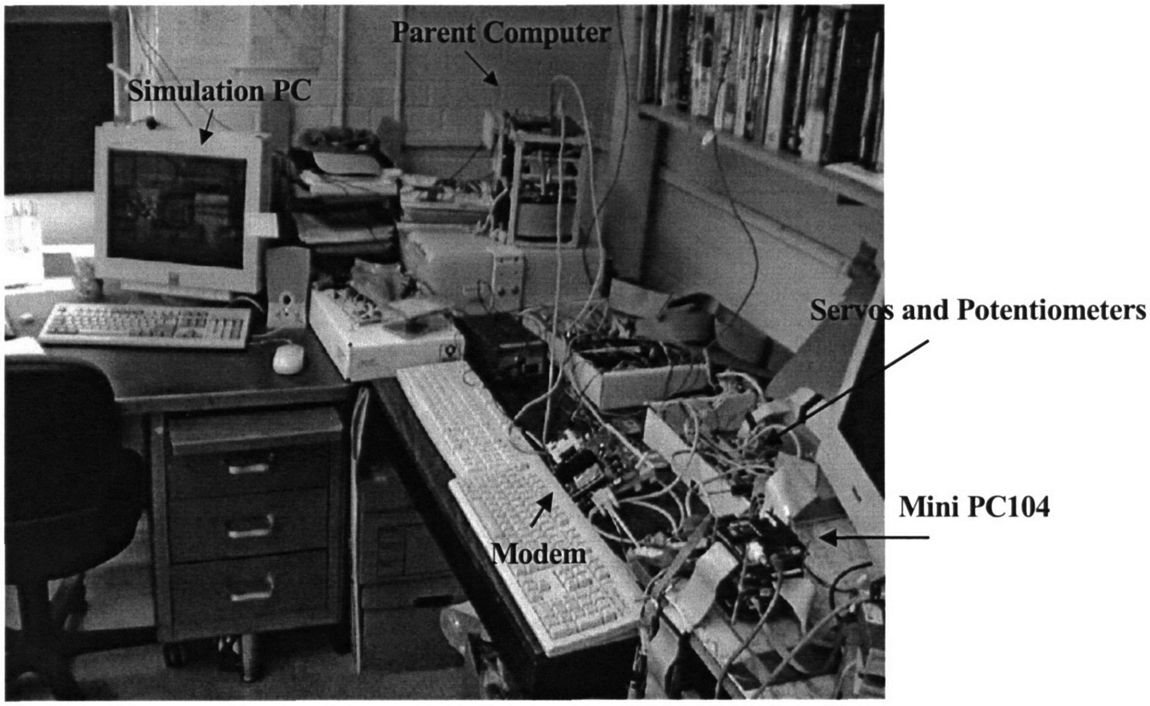


Figure B.3 Picture of the Hardware in the Loop Simulation

Appendix C

Alternate Phase I Strategy for Windy Conditions

The logic used by the author for Phase I in this thesis was based on the assumption that the future positions of the vehicles could be predicted more or less accurately. In Chapter 6, a strategy was described in which the wind was incorporated inside the synchronization. This model works for uniform and mild wind conditions, but if the vehicles are far apart, it is not reasonable anymore to assume that the wind condition they face are similar. Moreover, too much wind can saturate the airspeed commands as described in Chapter 6 and the synchronization is lost. This appendix briefly presents a possible solution for the Phase I of reintegration with a strong wind.

If the wind is strong, the synchronization cannot be done anymore by reasoning on ground speed. If the airspeed is used rather than the ground speed, a possible solution to synchronize the aircraft is the following. Since it is impossible to predict where the Parent will be on its circle at any future time, then the Mini first flies without taking the Parent information into account. Rather than directly arriving on the Parent circle, it aims at a circle of radius slightly larger than the Parent one, the synchronization circle. This is illustrated on Figure C.1.

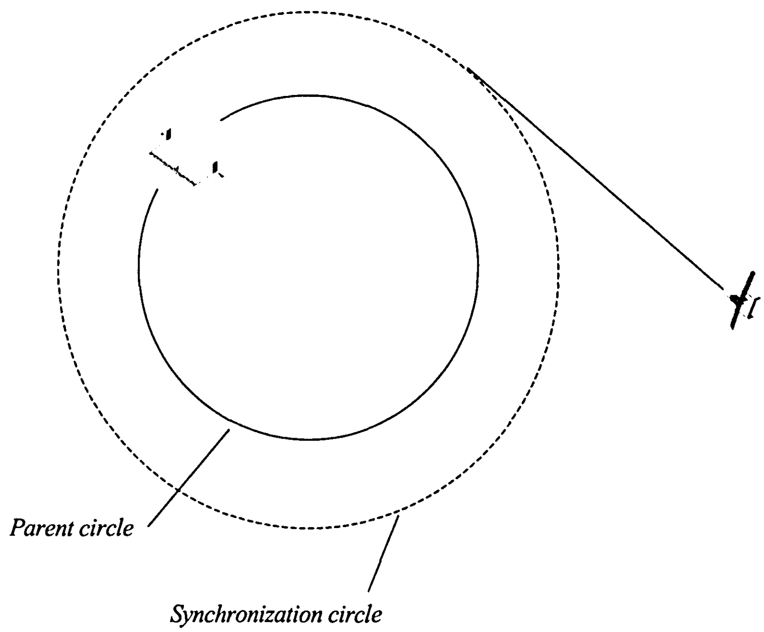


Figure C.1 Phase I using a synchronization circle

In order to reach this circle the approach is the same as the one described in 4.3.2 with three basic elements. Once the Mini is on the synchronization circle, it can begin to synchronize itself with the Parent. This would be done using velocity control; if the Parent is ahead, then the Mini accelerates while the Parent slows down. Once the Mini is side by side with the point 15m behind the Parent, it can start to navigate in the frame of reference linked to the Parent (Figure C.2). If the Parent is behind then the opposite happens.

A more efficient variant of this strategy would be to take the Parent information into account from the start. To get on the larger circle, the Mini would use a four step trajectory, and by calculating L_1 , it would determine the required trajectory to synchronize the two vehicles as if they kept the same ground speed. This is not the case since the speed velocity is controlled, but it would be an approximate estimation. This can help reduce the time required to perform Phase I.

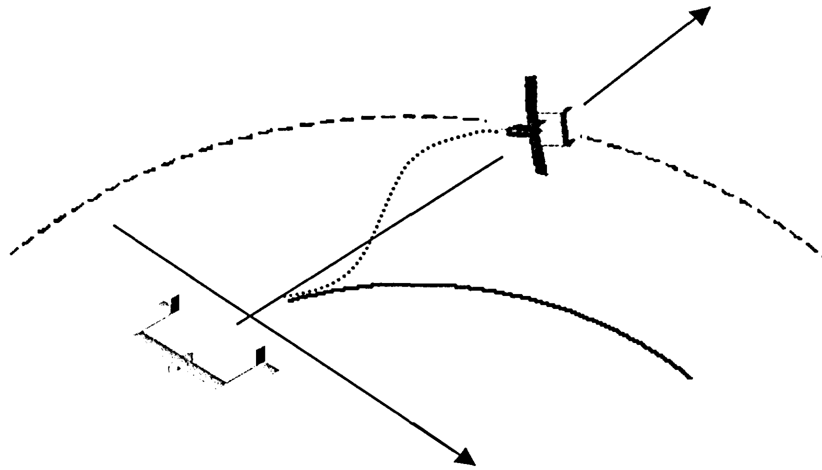


Figure C.2 Relative navigation of the Mini to reach the Parent circle

With a larger circle, the strategies described above would work even in adverse wind conditions, since in any case the Mini would be able to catch up with the Parent when it gets on the synchronization circle. However, for the demonstration of PCUAV, the flights take place in small wind conditions due to the nature of the aircraft - R/C airplanes are light and can only fly when the wind is gentle. These ideas, therefore, would apply for the objective system. For the PCUAV demonstration the synchronization circle strategy was abandoned.

Appendix D

Flight tests

D.1 Ground Station Display

As described earlier in Chapter 6, the flight information received on the Ground Station (GS) can be displayed on two different screens.

In the text mode, numbers are displayed on a black screen. More information can be displayed in this mode but the readability of the data is reduced. Moreover, some of these data need to be checked only once, when the flight computer is turned on. A picture of the GS in text mode is shown on Figure D.1.

The information displayed is:

- For the *Parent and the Mini* :
  - Position
  - Velocity vector components
  - Ground velocity, airspeed and the corresponding commands
  - Autonomy status
- For the *Mini*:
  - Information about the Phase I path (waypoints)
- For the *Parent*:

- Circle center coordinates;
- IMU information.

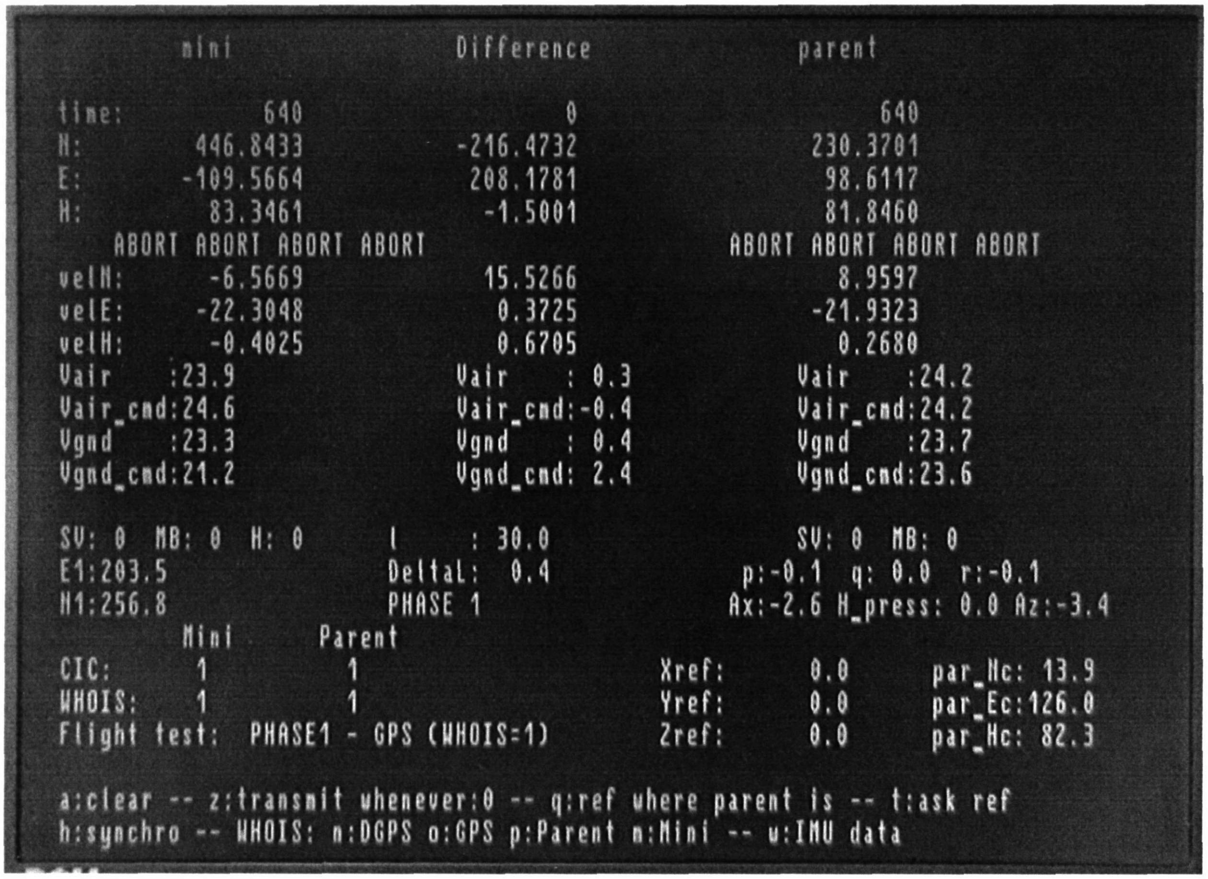


Figure D.1 Text Mode display on the GS

Note: This screen is from a hardware in the loop simulation and therefore no GPS infomation is available, hence the “ABORT“ printed on the screen.

During Phase I, the GS operators carry a lot of responsabilities since they must tell the pilots to take control of the aircraft should something go wrong. However, the large quantity of data to monitor makes it very hard to detect anomalies. This is why the team decided to create a graphical display. In this graphic mode, only the critical information is displayed, and an effort was made to avoid using numbers as much as possible. This graphic mode is shown on Figure D.2.

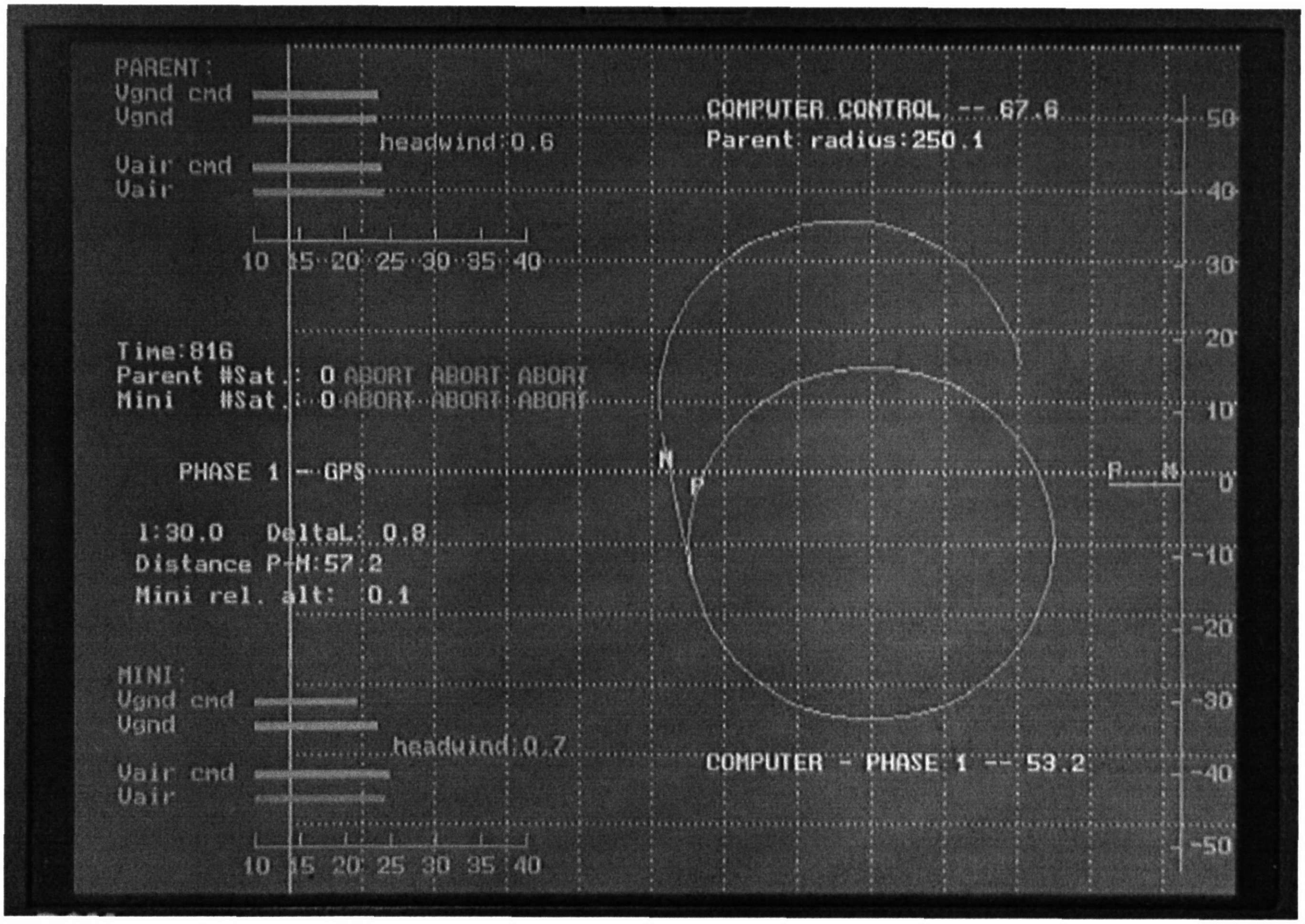


Figure D.2 Graphic Display on the GS

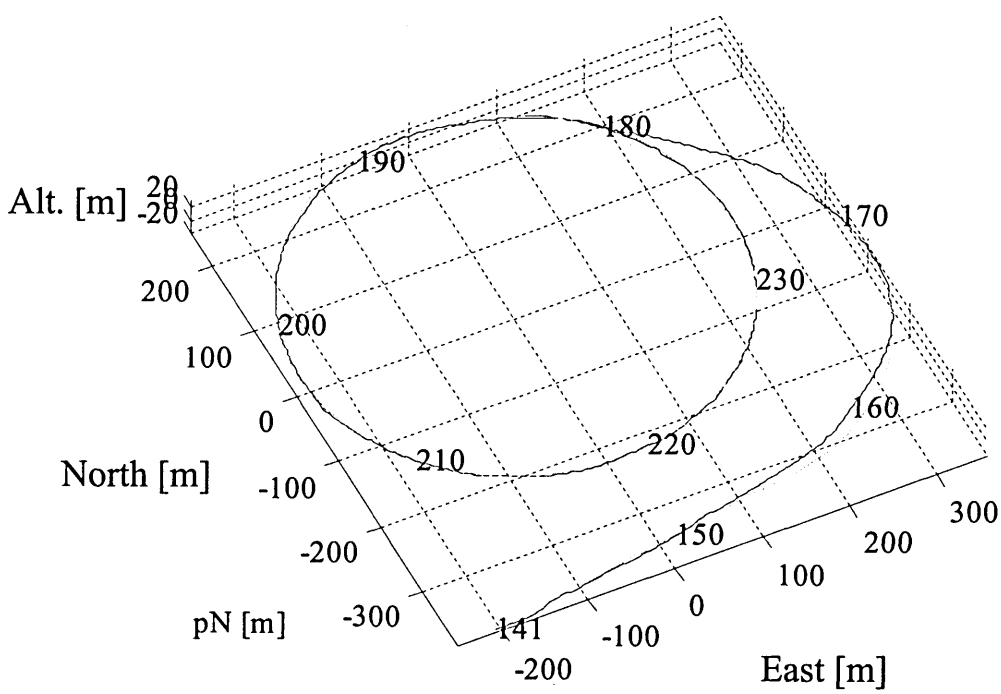
The graphic mode displays:

- The Parent ground velocity, airspeed and the respective commands in the form of horizontal bars. The airspeed, a critical parameter to prevent stalls, is plotted in a different color. An alert is displayed if the airspeed drops below 18m/s (top left);
- The Mini velocities (bottom left);

- The number of satellites that each vehicles onboard GPS tracks (below Parent velocities display). An alert is displayed if this number drops below 5;
- The information relevant for synchronization with the distance between Parent and Mini and relative altitude (above Mini velocities display);
- Whether or not each vehicle is autonomous (top and bottom right);
- The trajectories of the two vehicles and their current positions where M is the Mini and P is the Parent (center).
- The altitude differences between each vehicle altitude and their altitude reference. This is plotted with vertical bars (right);

D.2 Results of the Mini Autonomous Flight (March 8th, 2002)

This flight was to validate the Mini control system. The Mini was to create a Phase I path with four trajectory elements and navigate along it using PN and velocity control. The flight was successful, and the trajectory and velocity graphs are included below.



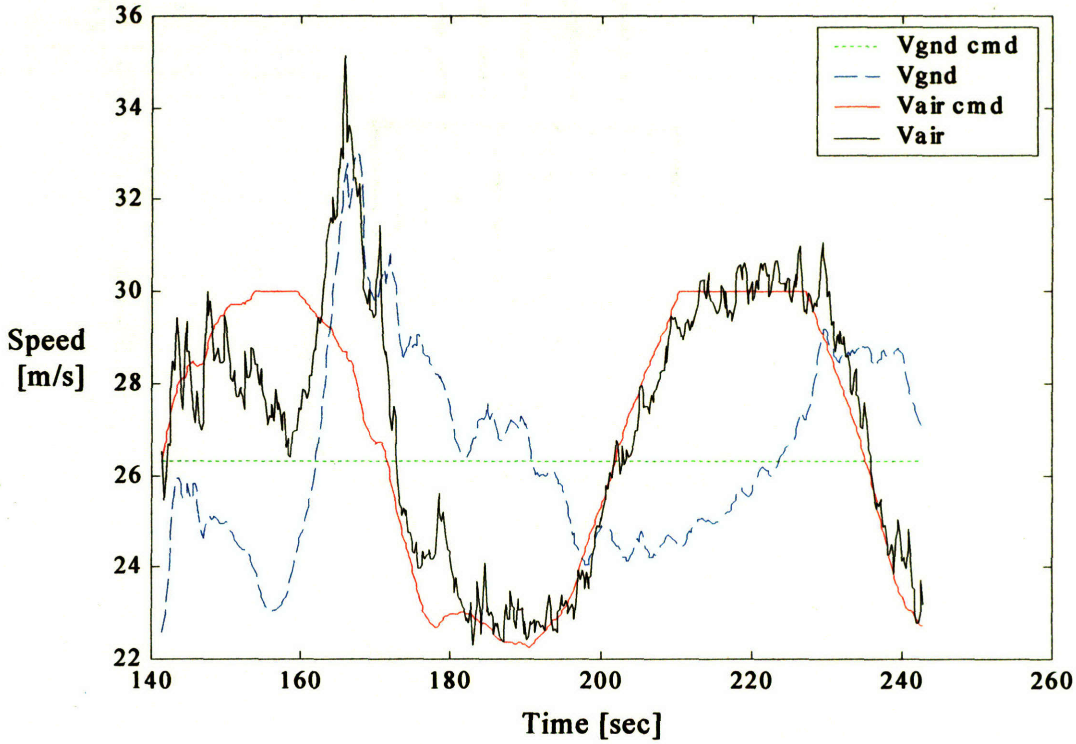


Figure D.3 Path (with time in seconds) and Velocity Graphs of the Mini (03/08/2002)

The velocity graph shows that the vehicle accurately followed the airspeed command which demonstrated that the synchronization could rely on the airspeed.

D.3 Results of the Parent First Autonomous Flight

On March 15th, 2002 the Parent flew autonomously for the first time. It followed a circle with a constant ground speed command. The unsual configuration of the aircraft and the flexibility of its tail booms were a challenge from a control point of view. Despite these singularities, the Parent flew very accurately along its path, holding its altitude within a few meters. The path is plotted on Figure D.4.

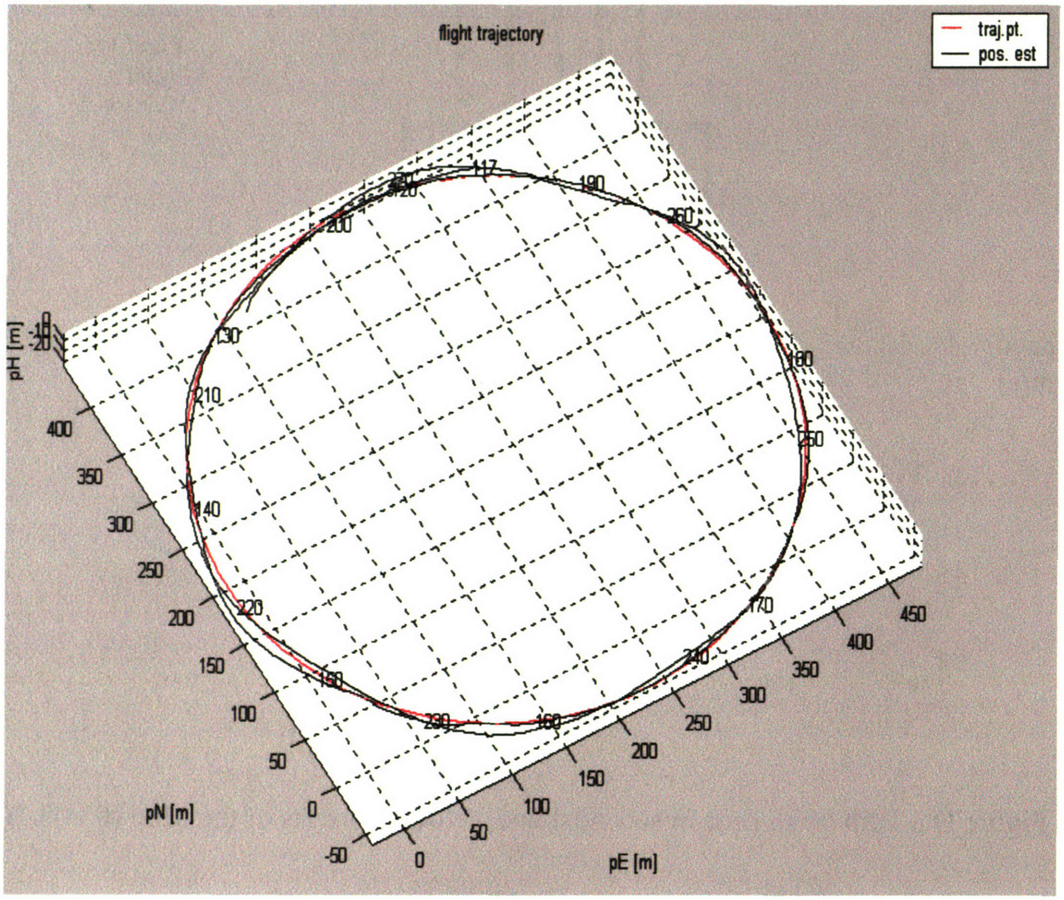


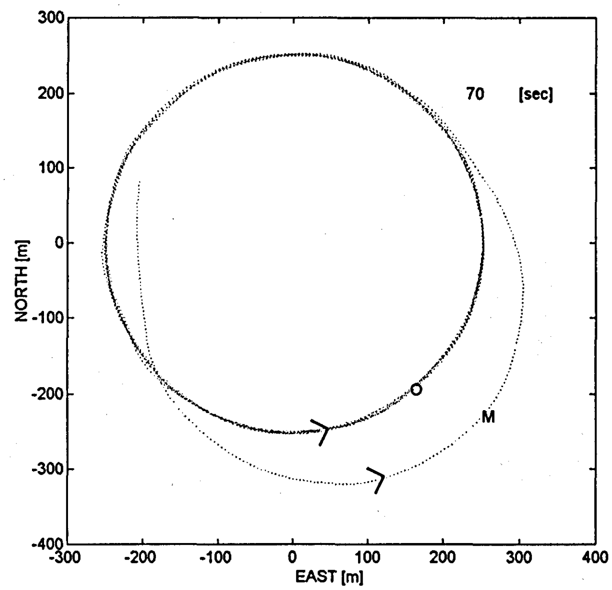
Figure D.4 Parent Flight Path (03/15/2002)

D.4 Results of Phase I tests

Once the autonomous control system of the two aircraft was validated the team decided to demonstrate Phase I.

Two attempts of Phase I were done within a week. They were both successful, although the first time (on July 18th, 2002), the altitude control of the Mini showed some instability. This problem was fixed, and the next attempt on July 25th, 2002 was a complete success. The two vehicles got within 12m of each other, exactly the range needed for the optical sensor used for Phase II.

On July 25th, 2002, two Phase I tests were performed. The trajectory of one was displayed in Chapter 6. They are both plotted below with the positions of the vehicles at a specific time before Phase I is completed (O is the Parent and M is the Mini).



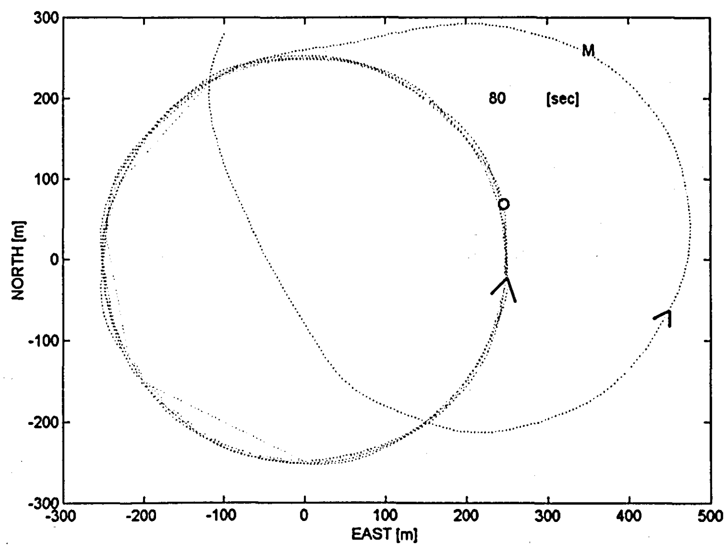


Figure D.5 Trajectories of the two Phase I tests attempted on July 25th, 2002

Once the Mini completed Phase I, it flew in formation flight behind the Parent on its circle, holding the separation distance. This initial distance between the two vehicles was about 30m, but the Mini copilot reduced it to about 12m. This distance is small enough for the range requirement of the Phase II optical sensor. The pictures below show the Parent and the Mini in formation flight approximately 15m away from each other. The first picture was taken from the ground, while the second picture was taken from a camera placed on the Parent, facing backwards.

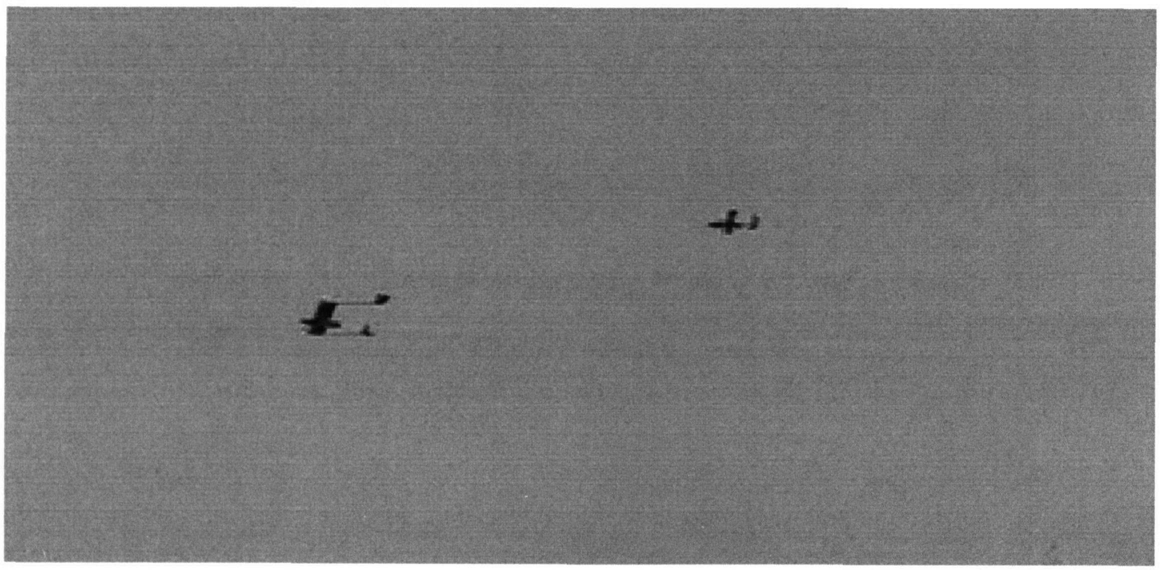


Figure D.6 Two aircraft in formation flight at the end of Phase I

Figure D.7 Mini viewed from the Parent rear Camera at the end of phase I